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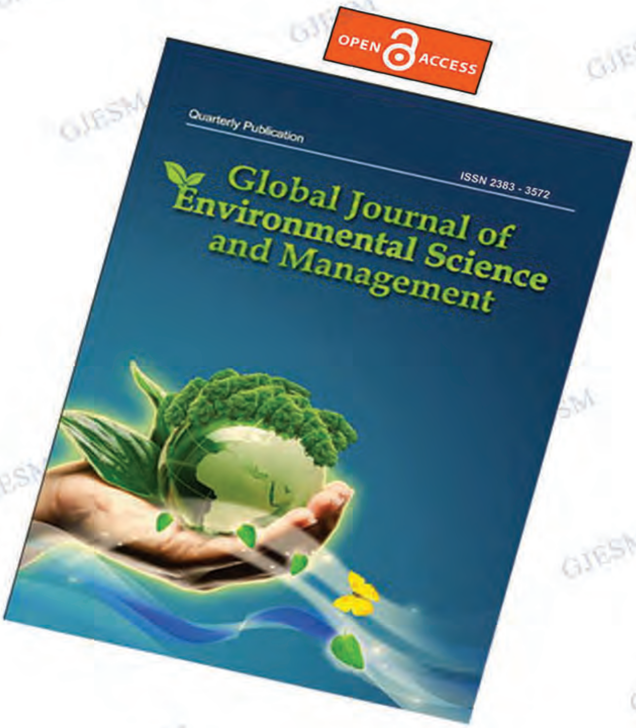

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ORIGINAL RESEARCH ARTICLE

Environmental awareness and plastic use behavior during the Covid-19 pandemic

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ABSTRACT

BACKGROUND AND OBJECTIVES: Plastic waste in Indonesia increased significantly during the Covid-19 pandemic. With this surge in plastic consumption and waste, awareness of environmental sanitation becomes essential, especially regarding the use of plastic. Society must consider the impact of single-use plastics and implement good plastic waste management. This study aimed to determine the environmental awareness of a community and what factors contributed to its plastic waste utilization activities during the Covid-19 pandemic.
METHODS: The data collection in this study was conducted using a questionnaire with a cross-sectional analytical approach. The study was conducted in Makassar City, South Sulawesi, the largest city in Eastern Indonesia, and purposive sampling was used to determine selected respondents. Data analysis was carried out using chi-square to identify partial relationships and logistic regression to distinguish relationships simultaneously.
FINDINGS: This study found that 53.2 percent of respondents frequently used plastic during the Covid-19 pandemic. Partial relationship analysis showed that general knowledge about waste and its impact was not significantly related to plastic use activities during the pandemic. Meanwhile, knowledge about plastic use during the pandemic, knowledge of protecting the environment, attitudes toward plastic use, attitudes toward waste management, behavior toward plastic use, and behavior regarding processing plastic waste were significantly related to plastic use activities during the Covid-19 pandemic, with respective test values of 0.000 each. Willingness to pay was also significantly related to plastic use activities during the pandemic, with a test value of 0.007. Simultaneous analysis showed that knowledge about plastic use during the pandemic was related to plastic use activities during the same time frame, with an odds ratio value of 0.398 and a negative relationship direction. Plastic waste-processing behavior was the most dominant factor influencing plastic use activities during the Covid-19 pandemic, with a test value of 0.000 and a positive relationship direction. Respondents who did not have good waste management behavior were 3.963 times more likely to use plastic frequently in their daily activities during the pandemic.
CONCLUSION: The study results show the importance of increasing knowledge regarding plastic use and waste management. Good knowledge will intervene in attitudes that encourage good behavior. This study focuses on the relationship between plastic processing behavior and the intensity of plastic use during the Covid-19 pandemic. It emphasizes the need for intervention in the form of education about the importance of protecting the environment and providing facilities that enable people to implement good waste-processing behavior.

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INTRODUCTION

The emergence of coronavirus disease 2019 (Covid-19) disrupted the usual course of human life and significantly changed people's lifestyles (Alzghoul *et al.,* 2022). Owing to this global health crisis, individuals were required to work from home (Igalavithana *et al.*, 2020), which, in turn, led to an increase in online orders for food and beverages. This situation occurred because people avoided gatherings with large crowds to avoid the Covid-19 virus. During the pandemic Covid-19, the use of single-use plastic (SUP) rose because of the assumption that plastic offers users protection against exposure to the Covid-19 virus, even though this virus can survive on plastic surfaces for up to 72 hours (Shekoohiyan *et al.*, 2022). Accordingly, one of the impacts of the Covid-19 pandemic is the increase in the consumption of plastic waste (Rai *et al*., 2022). Similarly, plastic use in Indonesia increased during the Covid-19 pandemic. In 2019, plastic waste was the third largest category of waste in Indonesia, accounting for 16.05 percent (%) of the country's total waste and totaling 4,739,684 tons. In 2020, amid the Covid-19 pandemic, this figure increased to 5,041,117 tons, pushing plastic waste (16.31%) to the second largest category at 16.31%, just behind food waste. Then, in 2021 and 2022, the use of plastic waste in Indonesia continued to increase, reaching 17.86% (5,280,702 tons) and 18.08% (6,500,458 tons), respectively, of the total waste generated in the country (SIPSN, 2023). Plastic is a versatile lightweight material that can be processed using various manufacturing techniques and has significant market potential. Plastics are polymer chains of monomers combined in repeating patterns. Fossil sources are converted into these macromolecules through various methods, such as polymerization, polycondensation, and polyaddition (Choudhury *et al*., 2022). Around 50% of the plastic produced is single-use plastic (Jahani *et al*., 2019). The increasing use of plastic has an impact on human life throughout the world (Abhilash and Inamdar, 2022). Previous research found that the increase in purchasing intensity is not linear with the level of waste recycling. Plastic products that are used only once before being thrown away, such as plastic bags, coffee cups, soda bottles, and water bottles, have meager recycling rates (12%) (Shams *et al*., 2021). Steps taken to control the Covid-19 pandemic have encouraged increased takeout food consumption, resulting in the use of SUP cutlery (Ho *et al*., 2023). The pandemic has caused a 5% to 10% increase in global plastic production, impacting soil quality through increasing microplastic (MPs) content. The increasing use of plastic waste contributes to land pollution and damage to marine ecosystems. Plastic pollution poses an environmental challenge because of the complexity of waste management and recycling, resulting in the accumulation of plastic waste. This situation will worsen environmental pollution (Rai *et al*., 2022). The global increase in plastic use during the Covid-19 pandemic contributed to heightened emissions of pollutants and greenhouse gases. It also fueled plastic pollution on both land and in the sea, endangering biodiversity and human health. Increasing plastic pollution is exacerbating future plastic problems, both on a small and large scale (Winton *et al.,* 2022). The main reasons for this environmental crisis are population density, high consumption of plastic products, and the inappropriate disposal of plastic waste (Van *et al*., 2020). Waste recycling is considered to reduce the amount of plastic waste pollution (Igalavithana *et al*., 2020). If recycling is carried out incorrectly, it will impact human health and the environment (Salhofer *et al*., 2021). Prior studies reported a minor decline in the frequency of trash disposal to collectors and recycling centers during the Covid-19 pandemic. Specifically, the percentage of individuals handing over waste to collectors decreased from 32.1% to 31.4%, while the percentage of individuals utilizing recycling facilities decreased from 24.2% to 19.8%. By contrast, after the occurrence of the pandemic, there was an observed increase in respondents' inclination toward the incineration of plastic garbage from 23.4% to 27.0% (Jayasinghe *et al*., 2022). Recycling plastic waste can be carried out using the Smart Waste application, which is used in the Philippines. This innovative application can detect how much plastic waste is collected in one waste container. After a large amount of waste has been collected in a trash can, the waste officer will dispose of the plastic waste through recycling (Sidhu *et al*., 2021). Another method for recycling SUP waste is via the reduce, reuse, recycle, and recover (4R) scheme (Mahmoudnia *et al*., 2022). Another waste management alternative is innovative waste technology, which utilizes near-field communication (NFC) from the user's smartphone. This technology can identify users through their user registration, and then the trash bin will sort the type of waste thrown away by the user. Collected and filled waste will be exchanged for compensation (Roche *et al*., 2021). Personal norms, which are shaped by environmental values and beliefs, are the main predictor of behavioral willingness. In campaign strategies, personal norms can be considered to change people's behavior in using reusable goods and products with plastic-free packaging alternatives (Shah *et al.,* 2023). A person's behavior will change if three elements are present, namely, ability, motivation, and opportunity (Allison *et al*., 2022). Moreover, the dominant factors influencing an individual's desire to process waste are the type of waste bin used, knowledge about how to manage waste and the dangers of poor waste management (Ssemugabo *et al*., 2020), location of residence, respondent's age, and knowledge on how to sort waste (Nsimbe *et al*., 2018). Previous research generally focused on the influence of demographic determinants (Choi *et al*., 2022), environmental impact analysis (Magni *et al.,* 2022), impact on marine animals (Eisfeld-Pierantonio *et al*., 2022), differences in waste quantity before and during the Covid-19 pandemic (Alazaiza *et al*., 2022), waste disposal behavior (Mejjad *et al*., 2021), technology for mitigating the impact of MPs (Zhao *et al.,* 2023), and production and management strategies (Liang *et al*., 2021). Behavioral influencing factors that are the source of the waste problem need to be researched and paid special attention. Therefore, the present study aims to determine the dominant factors that influence the use of plastic waste during the Covid-19 pandemic based on the aspects of knowledge, attitudes, and behavior. The main objective of this study is to explain how plastic utilization activities occurred during the Covid-19 pandemic. This study was conducted in Makassar, Indonesia in 2022.

MATERIALS AND METHODS

This cross-sectional analytical study aimed to identify the most dominant factors influencing plastic use activities during the Covid-19 pandemic based on the aspects of knowledge, attitudes, and behavior. The study was carried out in the urban area of Makassar City, Indonesia, in 2022. Makassar is a municipal entity that functions as the administrative center of South Sulawesi Province. It is regarded as one of the prominent urban centers in the nation of Indonesia. Makassar City is ranked as the fourth most populous city in Indonesia, and it holds the distinction of being the largest city within the Eastern Indonesia Region. Accordingly, the city holds the potential to produce large amounts of waste. Makassar consists of 15 sub-districts, namely, the districts of Biringkanaya, Tamalanrea, Manggala, Panakukang, Rappocini, Tallo, Wajo, Makassar, Ujung Pandang, Sangkarang, Mamajang, Ujung Tanah, Bontoala, Mariso, and Tamalate (Fig. 1).

Site and study sample

In this study, the sub-districts were categorized based on three groups: 1) groups with significant and developing populations, 2) groups categorized as saturated areas and business/shopping centers, and 3) coastal area groups. Group 1 consists of the Biringkanaya, Tamalanrea, Manggala, Panakukang, Rappocini, and Tallo district. Group 2 consists of the districts of Wajo, Makassar, and Ujung Pandang. Group 3 includes the Sangkarang, Mamajang, Ujung Tanah, Bontoala, Mariso, and Tamalate. Purposive sampling was conducted in these three groups. Biringkanaya District and Manggala District represent group 1. Wajo District represents the saturated sub-district group 2. The coastal area group 3 is represented by Ujung Tanah District and Mariso District. Except for the Manggala sub-districts, five sub-districts with the largest population were selected from the 15 sub-districts. Manggala District, which has the largest population in Makassar City, is represented by six sub-districts. Random sampling was used to determine the sample for this study. Specifically, the first sample was the first residence located to the right of the village head's office, the second sample used an interval of five households from the previous sample, and so on. Selected respondents were adults living in the selected households.

Data collection and survey

This study used a questionnaire instrument to collect data from respondents. The questionnaire consists of 1) respondent identity, 2) knowledge aspects, 3) attitude aspects, 4) behavior aspects, and 5) activity aspects of plastic use during the Covid-19 pandemic (Table 1). The knowledge aspect consists of four sub-aspects. (1) General knowledge about plastic, with the example statement "Plastic can be used for food packaging." (2) Knowledge of

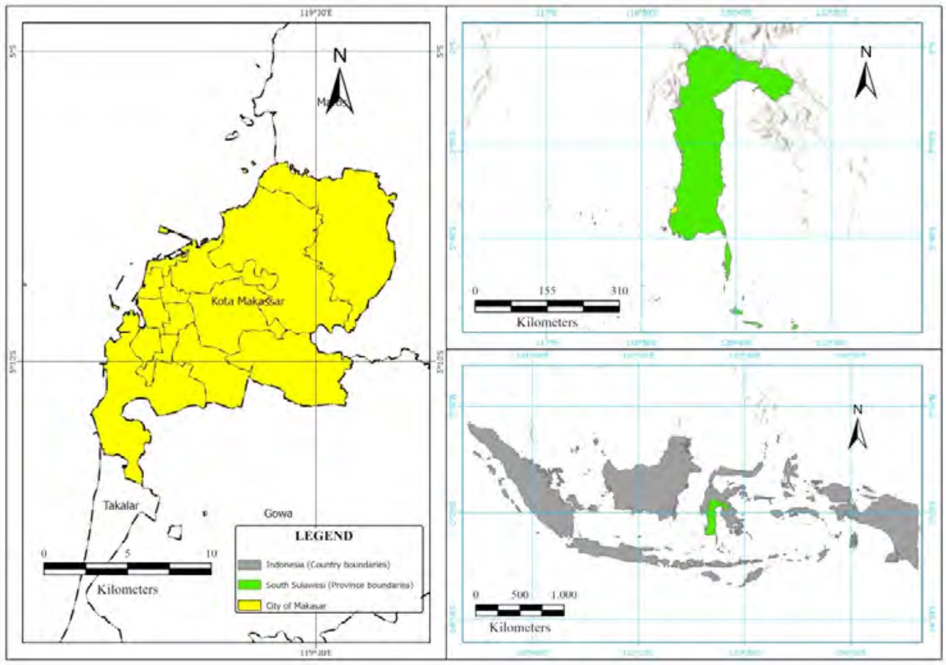

Fig. 1: Geographic location of the study area in Makassar City, South Sulawesi Province, Indonesia

Table 1: The study questionnaire

Questions	Answer	Measurement results
Respondent identity		
Education level	Graduated from college, graduated from college, graduated from high school, graduated from junior high school, graduated from elementary school, did not graduate from elementary school, or never went to school	-
Marital status	Single, married, divorced, or widow	
Frequency of drinks ordered online in a week	More than one time, only once, never	-
Plastic use activities during the Covid-19 pandemic	Always, almost always, sometimes, rarely, or never	Seldom or often
Knowledge		
General knowledge about waste	False or true	Poor or good
Knowledge of the impact of waste	False or true	Poor or good
Knowledge of protecting the environment	False or true	Poor or good
Knowledge about plastic during Covid-19	False or true	Poor or good
Attitude		
Waste management attitude	Strongly agree, agree, neutral, disagree, strongly disagree	Poor or good
Willingness to pay	Strongly agree, agree, neutral, disagree, strongly disagree	Willing or unwilling
Attitudes toward plastic use	Strongly agree, agree, neutral, disagree, strongly disagree	Poor or good
Behavior		
Plastic waste-processing behavior	Always, almost always, sometimes, rarely, or never	Poor or good
Plastic use behavior	Always, almost always, sometimes, rarely, or never	Poor or good

the impact of plastic on the environment, with the example statement "Plastic is a substance that is difficult to decompose/degrade in the environment." (3) Knowledge about plastic during the Covid-19 pandemic, with the example statement "The more often you change the plastic you use, the more you will reduce the risk of exposure to Covid-19." (4) Knowledge of protecting the environment, with the example statement "Plastic cups can be recycled to make crafts." Respondents' opinions regarding their general knowledge about plastic, knowledge of the impact of waste, knowledge of protecting the environment, and knowledge of plastic use during the Covid-19 pandemic received a value of 1 for "correct" answers and 0 for "wrong" ones. Meanwhile, in the attitude aspect, there are three sub-aspects. (1) The attitude toward plastic, with the example statement "For me, using shopping bags provides more comfort than using plastic." (2) Willingness to pay, with the example statement "I am willing to pay more for food packaging that is more environmentally friendly than using plastic." (3) The attitude toward waste management, with the example statement "In my opinion, plastic waste should not be thrown into the organic waste bin." Respondents' opinions regarding attitudes toward managing waste, willingness to pay, and attitudes toward using plastic received a score of 5 for "strongly agree," 4 for "agree," 3 for "neutral," 2 for "disagree," and 1 for "strongly disagree." In the behavioral aspect, there are two sub-aspects. (1) Plastic use behavior, with the example statement "I choose options with less plastic when shopping online." (2) Plastic waste management behavior, with the example statement "I recycle the plastic waste that I produce." Respondents' opinions regarding plastic waste-processing behavior and plastic use behavior received a score of 5 for "always," 4 for "almost always," 3 for "sometimes," 2 for "rarely," and 1 for "never." An example statement regarding the aspect of plastic use during the pandemic is "During the pandemic, I bought food with plastic packaging online." Respondents' opinions regarding plastic use activities during the Covid-19 pandemic received a score of 5 for "never," 4 for "rarely," 3 for "sometimes," 2 for "almost always," and 1 for "always."

Analysis procedures

Data analysis began with the editing, coding, and data entry stages. After the initial three stages were completed, the next stage was transforming or modifying the data. The dependent variable, namely, plastic use activities during the Covid-19 pandemic, was often or rarely measured. Meanwhile, the knowledge, attitude, and behavior variables have good or poor measurement results (Table 1). The measurement results of this study were categorized based on the skewness value. If the skewness value was in the range of minus (-) 2 to 2, the data were declared normally distributed so that the cut-off point was the mean value. On the other hand, if the skewness value was less than (<) -2 or more than (>) 2, then the data on that variable were not normally distributed, so the cut-off point used was the median value.

Statistical analysis

When data modification was completed, the data underwent univariate, bivariate, and multivariate analyses. The objective of univariate analysis is to ascertain the distribution of variables, which is typically given in the form of a frequency distribution table. In the context of statistical analysis, bivariate analysis employs the chi-square test to examine the partial association between dependent and independent variables. In this study, the chi-square test was also used to select candidate variables for inclusion in multivariate modeling with the condition that the p-value is less than or equal to (≤) 0.25. Binary logistic regression was also performed multivariate analysis. Model selection was carried out by entering all independent variables that met the p-value requirements for bivariate selection and then re-selecting variables that were not significant with a test value (p-value) > 0.05 (Samimi *et al.,* 2023). The final model included significant variables (p-value ≤ 0.05) to identify the independent variables with the most strongest relationship to the dependent variable (Samimi and Nouri, 2023). The entire data processing process used the Statistical Program for Social Science (SPSS).

RESULTS AND DISCUSSION

Table 2 shows that 228 (82%) respondents were married, and 129 (46.4%) had graduated from high school. A total of 142 (51.1%) respondents never ordered drinks online regularly during the week, while 95 (34.2%) respondents said they ordered drinks online more than once every week.

Table 2: Respondent characteristics

Respondent characteristics	Categories	Number (person)	Percentage (%)
Marital status	Single	38	13.7
	Married	228	82.0
	Divorced	4	1.4
	Widow	8	2.9
Education level	Never went to school	3	1.1
	Did not graduate from elementary school	3	1.1
	Graduated from elementary school	47	16.9
	Graduated from junior high school	47	16.9
	Graduated from high school	129	46.4
	Graduated from college	15	5.4
	Graduated from college	34	12.2
Frequency of drinks ordered online in a week	Never	142	51.1
	Only once	41	14.7
	More than one time	95	34.2

Table 3: Knowledge, attitudes, and behavior in using waste

Variables	Categories	Number (person)	Percentage (%)
Plastic use activities during the Covid-19 pandemic	Often	148	53.2
	Seldom	130	46.8
General knowledge about waste	Poor	147	52.9
	Good	131	47.1
Knowledge of the impact of waste	Poor	183	65.8
	Good	95	34.2
Knowledge of protecting the environment	Poor	134	48.2
	Good	144	51.8
Knowledge about plastic during Covid-19 pandemic	Poor	79	28.4
	Good	199	71.6
Waste management attitude	Poor	137	49.3
	Good	141	50.7
Willingness to pay	Unwilling	113	40.6
	Willing	165	59.4
Attitudes toward plastic use	Poor	122	43.9
	Good	156	56.1
Plastic waste-processing behavior	Poor	118	42.4
	Good	160	57.6
Plastic use behavior	Poor	148	53.2
	Good	130	46.8

Table 3 shows that 130 (46.8%) respondents said they seldom used plastic in their daily activities during the Covid-19 pandemic while 148 (53.2%) said they often used plastic. The majority of respondents (147, 52.9%) had poor general knowledge regarding waste, but 183 (65.8%) respondents had good knowledge about the impacts of waste. Meanwhile, 199 (71.6%) and 144 (51.8%) respondents had good knowledge regarding the use of plastic during the Covid-19 pandemic and protecting the environment, respectively. The majority of respondents' attitudes regarding waste processing were also predominantly good (141, 50.7%). Likewise, the willingness to pay additional expenses to use non-plastic containers was also dominant at 165 (59.4%) respondents. Attitudes toward plastic use were also predominantly good at 156 (56.1%) respondents. During the pandemic, many people thought leaving the house is the same as contracting the virus. Accordingly, the adoption of large-scale social restrictions (PSBB) led to a surge in online retail activities. This circumstance resulted in a notable escalation in the level of demand and utilization of SUP (Abhilash and Inamdar, 2022). The behavioral aspect of the current study shows that the majority of respondents (53.2%) did not have good plastic use behavior. Plastic use continued to increase during the Covid-19 pandemic because of its light weight, durability, and low production costs. These advantages make plastic, especially SUP, the ideal choice for everyday use, including for drinking water bottles and coffee cups (Mohana *et al*., 2023). Thus, people must be able to process waste, at least what they produce themselves. In this study, as many as 160 (57.6%) respondents had good behavior regarding waste processing during the pandemic.

Table 4 shows that general knowledge variables related to waste and its impact were not partially significantly related to plastic use activities during the Covid-19 pandemic. Most respondents (84, 57.1%) had poor general knowledge regarding waste and often used plastic during the pandemic. In addition, 95 (51.9%) respondents generally had poor knowledge of the impacts of waste and often used plastic. Seven other variables in this study were significantly related to plastic use activities during the pandemic. Knowledge of using plastic during the Covid-19 pandemic, knowledge of protecting the environment, and attitudes toward plastic use were significantly related to plastic use activities during the pandemic, each with p-value=0.000. The odds ratio (OR) value for knowledge of protecting the environment is 2.370, which means that respondents with poor knowledge had 2.370 times higher potential of using plastic frequently during the pandemic than the comparison group, namely, the respondents with good knowledge. This study aligns with previous research that states environmental awareness will either encourage or hinder community involvement in using plastic (Pocas and Selbourne, 2023). Public awareness can be increased through media channels, seminars, and workshops that involve and inspire communities to adopt zero-waste or sustainable packaging practices (Trubetskaya *et al*., 2022). Controlling plastic pollution is closely related to increasing the public's awareness to protect the environment and suppressing their desire to use plastic in their daily activities. Sun et al. (2023) stated that public attitudes are predominantly positive regarding the reuse of plastic but negative regarding waste collection and sorting activities. The community is also worried about the impact of indiscriminate burning and rubbish dumping, which will trigger air, water, and land pollution. The current research also found that the OR value of the relationship between knowledge of plastic use and plastic use activities during the Covid-19 pandemic was 3.345. This result means that respondents who had poor knowledge about plastic use were 3.345 times more likely to

Table 4: Results of Chi-Square analysis

Variables		Plastic use activities during the Covid-19 pandemic						p-value	OR
		Often		Seldom		Total			
		n	%	n	%	n	%		
General knowledge about waste	Poor	84	57.1	63	42.9	147	100	0.186	1.396
	Good	64	48.9	67	51.1	131	100		
Knowledge of the impact of waste	Poor	95	51.9	88	48.1	183	100	0.612	0.855
	Good	53	55.8	42	44.2	95	100		
Knowledge of protecting the environment	Poor	86	64.2	48	35.8	134	100	0.000	2.370
	Good	62	43.1	82	56.9	144	100		
Knowledge about plastic during the Covid-19 pandemic	Poor	58	73.4	21	26.6	79	100	0.000	3.345
	Good	90	45.2	109	54.8	199	100		
Waste management attitude	Poor	54	39.4	83	60.6	137	100	0.000	0.325
	Good	94	66.7	47	33.3	141	100		
Willingness to pay	Unwilling	49	43.4	64	56.6	113	100	0.007	0.510
	Willing	99	60	66	40	165	100		
Attitudes toward plastic use	Poor	48	39,3	74	60,7	122	100	0.000	0.363
	Good	100	64.1	56	35.9	156	100		
Plastic waste-processing behavior	Poor	38	32.3	80	67.8	118	100	0.000	0.216
	Good	110	68.8	50	31.3	160	100		
Plastic use behavior	Poor	59	39.9	89	60.1	148	100	0.000	0.305
	Good	89	68.5	41	31.5	130	100		

have frequent plastic use activities during the pandemic compared to those who had good knowledge. The results of this study are in line with those if previous research, which found that there was poor knowledge about various types of plastic materials and their impact on health (Pocas and Selbourne, 2023). This study also significantly related waste processing attitudes (p-value=0.000) to plastic use activities during the Covid-19 pandemic, with an OR value of 0.325. Most respondents (94, 66.7%) had good waste processing attitudes and frequent plastic use activities during the Covid-19 pandemic. Respondents with a poor attitude toward waste processing were 0.325 times more likely to use plastic in their activities during the pandemic compared to those who had a good attitude. The variable willingness to pay for plastic use activities during the pandemic was significantly but partially related (p-value=0.007), with OR=0.510. This result means that respondents unwilling to incur additional costs to avoid using plastic were 0.510 times more likely to use plastic during the Covid-19 pandemic than the comparison group. The majority (60%) of respondents often used plastic and were willing to pay additional costs to avoid using plastic. This finding contrasts with previous research by SSemugabo *et al*. (2020), who found that 67.1% of their respondents were unwilling to spend money to protect the environment related to waste issues. Abhilash and Inamdar (2022) also found that most respondents (58.4%) were unwilling to pay to avoid plastic use. Another attitude related to plastic use activities during the Covid-19 pandemic is attitudes toward plastic use. This study found that respondents who had a poor attitude toward the use of plastic were 0.363 times more likely (OR=0.363) to use plastic in their daily activities than the comparison group. This figure shows that respondents' knowledge regarding plastic utilization activities during the pandemic tended to be poor. However, most respondents had a good attitude. Individual knowledge and attitudes were found to be closely related. Previous research explained that individual attitudes can also be influenced by factors other than knowledge (Nsimbe *et al*., 2018). The present study found that the behavioral variables of plastic use and plastic waste processing were significantly related to plastic use activities during the Covid-19 pandemic, each with a p-value=0.000. The OR value for plastic use behavior is 0.305, and the OR value for plastic waste-processing behavior is 0.216. Respondents with poor use of plastic had the potential to frequently use plastic during the Covid-19 pandemic 0.305 times more compared to respondents with good behavior. Based on the results of this study, respondents continued to frequently use SUPs in their households during the pandemic. These findings are strengthened by previous research, which stated that 78.7% of respondents used plastic bags as waste containers (Ssemugabo *et al*., 2020). Other research also confirmed that most respondents, regardless of age, income level, or education, consume plastic products every day. As many as 18%–20% of urban, suburban, and rural respondents use plastic, grocery, and food bags in significant quantities. Before the Covid-19 pandemic, the most used SUP products were plastic shopping bags (35.2%), plastic food packaging (23.8%), and plastic bottles (21.5%) (Jayasinghe *et al*., 2022). The continuous increase in plastic waste indicates the importance of processing plastic waste. This study found that individuals with poor plastic waste-processing behavior were 0.216 times more likely to use plastic frequently during the Covid-19 pandemic than those with good knowledge (Table 3). Thus, a reorientation toward internal production is necessary because most plastics are not biodegradable. It is also important to note that plastic waste from the pandemic must be sterilized before being recycled (Abhilash and Inamdar, 2022). Regarding municipal waste management services, even though people's knowledge and attitudes regarding waste sorting are increasing, their motivation to sort waste is still relatively lower (Wang *et al*., 2022). There is no difference in waste management between SUP and other plastic packaging at the household level. Both types of plastic are regarded as waste made from the same polymers (Schmidt and Laner, 2021). The availability of alternatives to plastic is also an important focus. Previous research found that 83.33% of respondents chose to use plastic daily due to the lack of plastic alternatives (Bandara *et al*., 2023). The conditions that trigger the continuous use of plastic are then considered in developing strategies to change people's behavior. The plastic use behavior of the community can be positively influenced by increasing their knowledge and boosting public confidence to practice responsible plastic use, which, in the case of this study, is avoiding the use of SUP. Interventions can take the form of enhancing education, providing technical equipment that supports waste collection and sorting activities, and providing or facilitating access to plastic alternatives. Plastic waste can be minimized by recycling, although during the Covid-19 pandemic, recycling activities were difficult to carry out due to movement restrictions and other safety issues (Mohana *et al*., 2023). Recycling processes can be classified into four types: primary (a mechanical process is used to recycle plastic waste into products with the same properties as bare plastic), secondary (a mechanical process is used to recycle plastic waste into products with lower properties than the base plastic polymer), tertiary (a chemical process if used to reduce polymers into monomers/oligomers so they can be re-polymerized into new plastic products or used to make other types of materials), and quaternary (energy recovery in some forms of plastic processing) (Abhilash and Inamdar, 2022). The utilization of plastic trash as an energy source and the repurposing of used plastic objects into value synthetic products are effective solutions for the management of plastic waste. A waste management infrastructure must be established in order to effectively implement the 4R principles and ensure the appropriate exploitation of resources (Mahmoudnia *et al*., 2022). One way to reduce SUP is to reuse plastic bags (Gomes *et al*., 2022) or use reusable shopping bags (Amenábar *et al*., 2020). The use of reusable plastic will reduce the potential for health problems that arise due to plastic waste. Previous research found that reusable plastic should be used an average of 30 times to reduce the climate-change-based health impacts of SUP (Deeney *et al*., 2023). Plastic waste can also be reused in the construction industry. Using plastic waste can not only reduce the impact of plastic pollution but also limit excessive dredging of sand and other materials. Using 10% plastic mixture to replace cement can yield more robust construction results than not using any plastic waste in the mixture (Kamal *et al.,* 2023). Plastic waste from plastic bottles can also be used as road-paving material (Russo *et al.,* 2022). The use of plastic for asphalting has been around since the 1980s. From 2000 to 2022, asphalting as a form of processing plastic waste was a research topic in 412 studies (Ma *et al.,* 2023). Previous research found that using plastic waste as a paving material can help increase the durability and service life of asphalt for five years. Processing plastic as asphalt material is also considered to have minor consequences for human health and the ecosystem (Russo *et al.,* 2022). Other studies proposed the use of composting methods for processing plastic waste, but in practice, such methods cannot be applied to all types of plastic waste. This method can only be used on biodegradable plastics. The public is also required to participate in the sorting process, although previous research found that people's attitudes tend to be pessimistic regarding the sorting process (Sun *et al*., 2023). Choosing a composting method also requires government synergy to stimulate the public to sort waste that can go through the composting process, including by pressuring the industry to put recycling labels on plastics that can be recycled (Pocas and Selbourne, 2023).

This study also simultaneously analyzes the relationship between the dependent and independent variables through logistic regression (Table 5). It selects independent variables for logistic regression modeling using a p-value<0.25. The regression model does not include the knowledge variable regarding the impact of waste because it has a p-value>0.25. By contrast, the other eight variables are included in the regression model because they meet the p-value requirement of <0.25.

Table 5: Bivariate selection results

Independent variables	p-value
General knowledge about waste	0.186
Knowledge of the impact of waste	0.612
Knowledge of protecting the environment	0.000
Knowledge about using plastic during the Covid-19 pandemic	0.000
Waste management attitude	0.000
Willingness to pay	0.007
Attitudes toward plastic use	0.000
Plastic waste-processing behavior	0.000
Plastic use behavior	0.000

Table 6: The first model analysis results of logistic regression

Variables	Plastic use activities during the Covid-19 pandemic				
	B	SE	Wald	p-value	OR
General knowledge about waste	-0.137	0.274	0.251	0.617	0.872
Knowledge of protecting the environment	-0.417	0.285	2.141	0.143	0.659
Knowledge about using plastic during the Covid-19 pandemic	-0.663	0.338	3.853	0.05	0.515
Waste management attitude	0.211	0.327	0.417	0.518	1.235
Willingness to pay	-0.87	0.303	0.083	0.773	0.916
Attitudes toward plastic use	4.000	0.307	1.694	0.193	1.492
Plastic waste-processing behavior	0.968	0.346	7.817	0.005	2.634
Plastic use behavior	0.432	0.324	1.773	0.183	1.540
Constant	-0.586	0.332	3.110	0.078	0.557

Table 7: Final model analysis results of logistic regression

Variables	Plastic use activities during the Covid-19 pandemic				
	B	SE	Wald	p-value	OR
Knowledge about using plastic during the Covid-19 pandemic	-0.920	0.308	8.930	0.003	0.398
Plastic waste-processing behavior	1.377	0.267	26.573	0.000	3.963
Constant	-0.477	0.196	5.936	0.015	0.621

The results of the logistic regression in the initial modeling are shown in Table 6. The variable general knowledge about waste has a p-value=0.617. It does not meet the p-value<0.05, so it is declared not significantly related to plastic use activities during the Covid-19 pandemic. The variable knowledge of plastic use was simultaneously related to plastic use activities during the Covid-19 pandemic (p-value=0.05), with an OR=0.515. This result means that with other variables, respondents with poor knowledge regarding plastic use had the potential to use plastic 0.515 times in their daily activities during the Covid-19 pandemic. Three variables related to attitude, namely, attitude toward processing waste (p-value=0.518), willingness to pay (p-value=0.773), and attitude toward plastic use (p-value=0.193), did not have a significant influence on plastic. Waste-processing behavior was stated to be simultaneously related to plastic use activities during the Covid-19 pandemic, with a value of p=0.005. The modeling results show that respondents who misbehaved in managing waste were 2.634 times more likely to use plastic daily during the pandemic. The behavioral factor variable using waste was also not simultaneously significantly related to plastic use activities during the Covid-19 pandemic with p-value = 0.183 (Table 6).

Table 6 shows two variables significant to plastic use activities during the Covid-19 pandemic in the model. The next step is to look at the most dominant determinants influencing plastic use activities during the Covid-19 pandemic through final modeling, which contains the significant variables in the first modeling. The final modeling results are presented in Table 7.

Based on Table 7, the association between plastic use during the Covid-19 pandemic and the level of knowledge regarding plastic use was statistically significant (p=0.003). The OR of 0.398 suggests a negative relationship between plastic use activities during the pandemic and knowledge. This is further supported by the negative beta coefficient (B) of -0.920. Concurrently, there existed a correlation between behavioral aspects in plastic waste processing and the most recent modeling of plastic use patterns amid the Covid-19 pandemic, as indicated by a statistically significant p-value of 0.000. The plastic waste management behavior variable exhibits a strong positive connection (B=1.377) and OR=3.968, making it the primary determinant of plastic use behaviors during the pandemic. This implies that individuals who exhibited inadequate waste management practices were 3.968 times more likely to engage in regular plastic usage in their daily routines during the pandemic compared to individuals who demonstrated effective waste management practices. The consideration of recycling both medicinal and non-medical waste is imperative to uphold public health and mitigate potential environmental hazards within the ongoing Covid-19 pandemic (Shekoohiyan *et al*., 2022). In the "new normal" era, efforts to find solutions to excessive consumption and production of plastic waste, unsustainable use, and management of plastic are becoming increasingly urgent (Winton *et al*., 2022). Continuous use of plastic without proper processing and management will trigger plastic pollution (Mukhtar *et al*., 2023). Before the Covid-19 pandemic, SUP waste was considered a major environmental problem in land and marine ecosystems. The global impact of plastic pollution has a detrimental impact on flora and fauna, social welfare, and public health. Plastic waste is known to cause environmental stress, adding micropollutants to world ecosystems that are vulnerable and stressed by change (Jayasinghe *et al.,* 2022). Previous research explains that most plastics are burned, resulting in more significant pollution (Sun *et al.,* 2023). Poor waste management can be the root of many health and environmental problems, from the spread of disease to the increased release of new pollutants (such as MPs) into the environment (Mahmoudnia *et al.,* 2022). Plastic generally ends up in landfills and is difficult to biodegrade, leading to dirty environmental conditions. Plastic waste has the potential to block sewer lines and drainage systems, which facilitates the breeding of disease agents such as mosquitoes. This condition can also be a means for the growth of other pathogens that cause malaria, cholera, typhus, diarrhea, and other diseases (Mukhtar *et al*., 2023). Therefore, drastic measures are needed to reduce the amount of plastic pollution (Van Rensburg *et al.,* 2020). The ineffectiveness and inadequacy of current waste management systems and the lack of proper enforcement of environmental regulations, post-pandemic mishandling of plastic waste have escalated rapidly, causing severe environmental impacts (Raja *et al.,* 2020). Climate change and the emergence of particulate matter are the most influential impact categories in all waste processing scenarios considered, amounting to 74%–76% of the total environmental impact. Environmental pollution, including plastic pollution in land, air, and water environments, is also the cause of toxicity in humans, amounting to 20%–22% of the total toxicity cases (Bracquené *et al*., 2021). Facility closures during the pandemic also had a significant impact on plastic recycling facilities around the world. This condition resulted in the inappropriate and illegal dumping of plastic waste into the sea and land (Shams *et al*., 2021). The dominance of online plastic packaging sales likewise causes plastic waste accumulation. The increase in the amount of waste contradicts the public's desire to recycle waste (Abhilash and Inamdar, 2022). One solution can be offered by increasing public knowledge regarding efficient waste management. Public knowledge about efficient waste management will encourage the community to participate in waste management. Besides encouraging positive societal decisions, efficient waste management will reduce waste pollution and save costs (Fadhullah *et al*., 2022). During the Covid-19 outbreak, there has been a notable surge in the utilization of personal protective equipment (PPE) and disposable plastic items. The condition bears consequences for plastic garbage, as the improper handling of such items poses a growing risk of environmental harm. Bio-based or biodegradable plastics have the potential to serve as a feasible substitute for synthetic polymer plastics. The global rental production capacity for biodegradable or bio-based plastic is presently limited to a mere 4 million tons. Developing biodegradable plastic materials, such as face masks, has become essential and has achieved significant development progress. The substitution of these commodities with synthetic plastics constitutes a crucial measure in mitigating the environmental repercussions of the pandemic (Mahmoudnia *et al*., 2022). Individual motivation can encourage individuals to take the initiative to carry out behavior, but external motivation will encourage them to improve behavior for external rewards and pressure. Self-motivation can continue to improve and maintain waste-sorting behavior to a certain level (Wang *et al*., 2022). Recycling SUP waste is a difficult task because the composition of plastic itself is complex (Bracquené *et al*., 2021). Therefore, people need to be aware of the use of SUP and switch to shopping bags that can be used many times. Based on previous research, the composition of plastic waste produced by households in one region in Malaysia reached 19%. The study also explains that locality is a significant factor related to perceptions of waste management, with a p-value of 0.04 (p-value<0.05). Most respondents (80.2%) believe that plastic recycling is a way to increase economic development (improving economic and social welfare), and 79.3% believe that increasing plastic recycling will create new jobs (Roche *et al*., 2021). The results of this study and the scientific debate with previous research show the importance of increasing public knowledge regarding waste in general to include knowledge regarding waste during the Covid-19 pandemic. Basic knowledge regarding waste and knowledge that focuses on the reality faced by society, namely, the Covid-19 pandemic conditions, will encourage positive attitudes and behavior in protecting the environment through controlling decisions in using plastic waste. Continuous training can increase knowledge so that the entire community can manage waste well. If this training can be carried out in the household environment, it can motivate people to control the accumulation of household waste (Fadhullah *et al*., 2022). The community must also be motivated to protect the surrounding environment from plastic pollution (Shekoohiyan *et al*., 2022). Attitudes and knowledge can change if they get motivation from the social environment. Therefore, if the community can behave well toward the use of plastic, then a person's attitude will also be good toward the perception of the use of SUP (Wang *et al*., 2022). A person's behavior will change if there are three elements present within them, namely, ability, motivation, and opportunity (Allison *et al*., 2022). Meanwhile, some motivation itself comes from within the individual, and some from outside the environment (Wang *et al.,* 2022). This finding is reinforced by other research showing that a combination of skills, opportunities, and motivation is required to implement behavior, indicating the need for a holistic approach to intervention design (Winton *et al*., 2022). The government is an essential actor in stimulating people's desire to be able to process and manage plastic. According to Pocas and Selbourne (2023), the government is the actor most responsible for information regarding the benefits of plastic for society as consumers. The government can formulate regulations that pressure business actors to use plastic that can be recycled or reused, as is done in European countries (Pocas and Selbourne, 2023). In 2020, China introduced policies to reduce plastic consumption and encourage a more environmentally friendly lifestyle by gradually banning or limiting the production, sale, and use of several actively promoted plastic products (Sun *et al.,* 2023). The Indonesian government has emphasized that the implementation of waste management can be carried out by district/city governments by establishing waste management policies and strategies based on provincial and national policies. In Law Number 18 of 2008, district/city governments have the authority to develop and supervise the performance of waste management carried out by other parties. Regional governments also have the authority to determine the location of temporary storage areas, integrated waste processing sites, and/or final waste processing sites. Law Number 18 of 2008 also explains the community's obligation to manage household waste, including reducing and handling waste in an environmentally sound manner. Manufacturers are also encouraged to include labels on packaging, with the aim of making it easier to sort and handle waste, including plastic. This law emphasizes that producers must manage the packaging and/or goods they produce that cannot or are difficult to decompose by natural processes. The Republic of Indonesia Government Regulation Number 81 of 2012 concerning the Management of Household Waste and Similar Household Waste reaffirms the role of producers in managing plastic. Producers must develop plans or programs to limit waste generation and use packaging that is easily decomposed in nature and produces as little waste as possible (Pemerintah Indonesia, 2012). Republic of Indonesia Government Regulation Number 27 of 2020 concerning Special Waste Management, including Plastic, also states that waste management is done through reduction and handling. This reduction limits the generation of specific waste, recycles specific waste, and reuses plastic waste. Meanwhile, the handling referred to in government regulations is sorting, collecting, transporting, processing, and final waste processing (Pemerintah Indonesia, 2020). Indonesian government regulations cover various waste issues, from processing, management, and use to emphasizing different responsibilities for each element of society. Good regulations then require appropriate implementation accompanied by monitoring and evaluation, as also contained in the regulations. Previous research states that the supervision, monitoring, and evaluation process carried out by the government can be influenced by systemic challenges, such as ineffective communication and top-down policies (Trubetskaya *et al*., 2022). The government can also start increasing monitoring and evaluation of programs that have been designed as permitted by regulations in Indonesia. Furthermore, it can use the results of this research as a consideration in designing programs by focusing on increasing knowledge about the use of plastic and plastic waste management behavior.

CONCLUSION

This study explains plastic utilization activities during the Covid-19 pandemic. Plastic use during the pandemic was largely prevalent (53.2%) among the general population. A significant proportion of individuals lacked enough understanding of waste in a broader context, with 52.9% exhibiting limited knowledge. A considerable majority (65.8%) likewise possessed insufficient awareness regarding the ramifications associated with the utilization of plastic materials. By contrast, a significant proportion of the general population possessed a commendable level of understanding pertaining to the use of plastic materials amid the pandemic, with 71.6% demonstrating awareness in this regard. Additionally, a noteworthy percentage of individuals (51.8%) exhibited a commendable level of knowledge concerning the safeguarding of the environment during the pandemic. Community attitudes tend to be good in using plastic waste (56.1%), willingness to pay (59.4%), and waste management (50.7%). The majority of waste usage behavior was poor at 53.2%, whereas waste management behavior tended to be good at 57.6%. General knowledge about waste (p-value=0186) and the impact of waste (p-value=0.612) were not significant on plastic use activities during the Covid-19 pandemic. Partially, knowledge about plastic during the Covid-19 pandemic (OR=3.345), knowledge of maintaining the environment (OR=2.370), plastic use attitudes (OR=0.363), waste management attitudes (OR=0.325), plastic use behavior (OR=0.305), and plastic waste management behavior (OR=0.216) were significantly related to plastic use activities during the pandemic, with each having a p-value=0.000. Willingness to pay was also partially related to plastic use activities during the pandemic, with p-value=0.007 and OR=0.510. Simultaneously, knowledge about plastic was significantly related to plastic use activities during the Covid-19 pandemic (p-value=0.003), with OR=0.398, and the direction of the relationship was negative (B=-0.920). Plastic waste management behavior was the dominant factor influencing plastic use activities during the pandemic (p-value=0.000). Individuals with poor plastic waste management behavior had 3.963 times more significant potential to frequently use plastic in their daily activities than those with good behavior in managing plastic waste. Plastic consumption has increased since the Covid-19 pandemic. This situation happened because of changes in human lifestyle during the pandemic, cheap prices, and easy access. Plastic pollution has various impacts, both on environmental health and human health. Several actions can be taken to address potential adverse impacts, starting with selective delivery of materials to recycling sites and improvements to the sorting stage. This research recognizes the need to deepen the community's barriers to good plastic use and management behavior. However, this research is limited to behavioral determinant factors, namely, attitudes, knowledge, and actions. It is hoped that future research can further explore the determinants of individual behavior by using different perspectives, such as the health belief model. This model can dissect individual perceptions from various aspects, including perceived barriers and perceived benefits, which are not the focus of the current research. Future research can also collect information through a qualitative approach to find in-depth information.

AUTHOR CONTRIBUTIONS

H. Herdiansyah, the corresponding author, was responsible for supervising the study, obtaining funding, conceptualizing the research, developing the methodology, and preparing the resources. Nuraeni participated in writing the original draft, reviewing and editing, preparing pictures, analyzing the data, interpreting the results, preparing the tables of study results, and drawing conclusions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

>	More than
≤	Less than or equal to
<	Less than
%	Percent
-	Minus
–	Until
4R	Reduce, reuse, recycle, and recover
B	Beta coefficient
Covid-19	Coronavirus disease 2019
MP	Microplastic
NFC	Near-field communication
OR	Odd ratio
p-value	The probability under the assumption of no effect or no difference
PPE	Personal protective equipment
PSBB	Pembatasan Sosial Berskala Besar (Large-Scale Social Restrictions)
SE	Standard Error
SIPSN	Sistem Informasi Pengelolaan Sampah Nasional (National Waste Management Information System)
SPSS	Statistical Program for Social Science
SUP	Single-use plastic

REFERENCES

Abhilash; Inamdar, I., (2022). Recycling of plastic wastes generated from COVID-19: A comprehensive illustration of type and properties of plastics with remedial options. Sci. Total Environ., 838: 155895 **(20 pages)**.

Alazaiza, M.; Abdelfattah, F.; Almaskari, T.; Bashir, M.; Nassani, D.; Albahanasawi, A.; Abushammala, M., (2022). Effect of COVID-19 Pandemic on Food Purchasing and Waste Generation during the Lockdown Period in The Sultanate of Oman. Global NEST J., 2(1): 59-64 **(6 pages).**

Allison, A.L.; Baird, H.M.; Lorencatto, F.; Webb, T.L.; Michie, S., (2022). Reducing plastic waste: A meta-analysis of influences on behaviour and interventions. J. Cleaner Prod., 380: 134860 **(18 pages).**

Alzghoul, S.E.; Smadi, O.A.; Almomani, T.D.; Alzghoul, M.B.; Albataineh, O.M., (2022). Solid medical waste management practices and awareness in COVID-19 screening stations Global J. Environ. Sci. Manage., 8(3): 327-338 **(12 pages).**

Amenábar C.M.; Holzapfel, C.; Nehls, M.; De Veer, D.; Gonzalez, C.; Holtmann, G.; Honorato-Zimmer, D.; Kiessling, T.; Muñoz, A.L.; Reyes, S.N.; Nuñez, P.; Sepulveda, J.M.; Vásquez, N.; Thiel, M., (2020). The rise and demise of plastic shopping bags in Chile – Broad and informal coalition supporting ban as a first step to reduce single-use plastics. Ocean Coastal Manage., 187: 105079 **(13 pages)**.

Bandara, L.D.; Marasinghe, K.I.; Mahagamage, Y.L., (2023). The usage of household polythene and its management approaches. Environ. Qual. Manage., 00: 1–11 **(9 pages)**.

Bracquené, E.; Martinez, M.G.; Wagner, E.; Wagner, F.; Boudewijn, A.; Peeters, J.; Duflou, J., (2021). Quantifying the environmental impact of clustering strategies in waste management: A case study for plastic recycling from large household appliances. Waste Manage., 126: 497–507 **(11 pages)**.

Choi, E.-H.; Lee, H.; Kang, M.-J.; Nam, I.; Moon, H.-K.; Sung, J.-W.; Eu, J.-Y.; Lee, H.-B., (2022). Factors Affecting Zero-Waste Behaviours of College Students. Int. J. Environ. Res. Public Health, 19: 9697 **(11 pages).**

Choudhury, M.; Sahoo, S.; Samanta, P.; Tiwari, A.; Tiwari, A.; Chadha, U.; Bhardwaj, P.; Nalluri, A.; Eticha, T.K.; Chakravorty, A., (2022). COVID-19: An Accelerator for Global Plastic Consumption and Its Implications. J. Environ. Public Health. 2022: 1066350 **(17 pages)**.

Deeney, M.; Green, R.; Yan, X.; Dooley, C.; Yates, J.; Rolker, H.B.;

Kadiyala, S., (2023). Human health effects of recycling and reusing food sector consumer plastics: A systematic review and meta-analysis of life cycle assessments. J. Prod., 397: 136567 **(16 pages).**

Eisfeld-Pierantonio, S.M.; Pierantonio, N.; Simmonds, M.P., (2022). The impact of marine debris on cetaceans with consideration of plastics generated by the COVID-19 pandemic. Environ. Pollut., 300: 118967 **(14 pages)**.

Fadhullah, W.; Imran, N.I.N.; Ismail, S.N.S.; Jaafar, M.H.; Abdullah, H., (2022). Household solid waste management practices and perceptions among residents in the East Coast of Malaysia. BMC Public Health. 22(1): 1–20 **(20 pages)**.

Gomes, A.R.; Lazaro, J.C.; Leocadio, A., (2022). Should I Reuse It or Throw It Out? Analysis of the Management of Household Plastic Waste by Brazilian Consumers during the COVID-19 Pandemic through Practice Lens. Sustainability (Switzerland), 14(14): 8512 **(12 pages)**.

Igalavithana, A.D.; Yuan, X.; Attanayake, C.P.; Wang, S., (2020). Sustainable management of plastic wastes in COVID-19 pandemic: The biochar solution. Environ. Res., 212: 113495 **(13 pages).**

Jahani, A.; Dehdari, T.; Farzadkia, M.; Mansourian, M., (2019). Iranian experiences in terms of consumption of disposable single-use plastics: Introduction to theoretical variables for developing environmental health promotion efforts. Environ. Toxicol. Pharmacol., 65: 18–22 **(5 pages)**.

Jayasinghe, R.R.; Abeyrathna, W.P.; Lythgoe, D.; Hendawitharana, M.P.; Liyanage, C.; Williams, K.; Halwatura, R.U., (2022). Analysis of the community behavioural patterns in management of household plastic waste due to the COVID-19 pandemic in Sri Lanka. Case Stud. Chem. Environ. Eng., 6: 100246 **(7 pages)**.

Kamal, M.A.; Moussa, R.R.; Guigus, M.N., (2021). Recycled Plastic as an Aggregate in Concrete 6 pages. Civ. Eng. Archit., 9(5): 1289-1294 **(6 pages).**

Liang, Y.; Song, Q.; Wu, N.; Li, J.; Zhong, Y.; Zeng, W., (2021). Repercussions of COVID-19 pandemic on solid waste generation and management strategies. Front. Environ. Sci. Eng. 15: 115 **(18 pages).**

Ma, J.; Nawarathna, H.M.C.; Hesp, S.A.M., (2022). On the sustainable use of recycled plastics in flexible asphalt pavements. J. Cleaner Prod., 359: 132081 **(2022).**

Magni, S.; Della T.C.; Nigro, L.; Binelli, A., (2022). Can COVID-19 pandemic change plastic contamination? The Case study of seven watercourses in the metropolitan city of Milan (N. Italy). Sci. Total Environ., 831: 154923 **(12 pages).**

Mahmoudnia, A.; Mehrdadi, N.; Golbabaei K.F.; Rahmati Deiranloei, M.; Al-e-Ahmad, E., (2022). Increased personal protective equipment consumption during the COVID-19 pandemic: An emerging concern on the urban waste management and strategies to reduce the environmental impact. J. Hazard. Mater. Adv., 7: 100109 **(6 pages)**.

Mejjad, N.; Cherif, EK; Rodero, A.; Krawczyk, DA; El Kharraz, J.; Moumen, A.; Laqbaqbi, M.; Fekri, A., (2021) Disposal Behavior of Used Masks during the COVID-19 Pandemic in the Moroccan Community: Potential Environmental Impact. Int. J. Environ. Res. Public Health, 18: 4382 **(19 pages).**

Mohana, A.A.; Islam, M.M.; Rahman, M.; Pramanik, S.K.; Haque, N.; Gao, L.; Pramanik, B.K., (2023). Generation and consequence of nano/microplastics from medical waste and household plastic during the COVID-19 pandemic. Chemosphere. 311: 137014 **(13 pages)**.

Mukhtar, S.; Asad, A.; Mumtaz, M.; Saeed, A.U.; Qadir, a.; Ahmad, S.R.; Saeed, H.F.U., (2023). Role of knowledge and attitude of public and private school students for plastic pollution awareness, usage, and management in Lahore, Pakistan. J. Mater. Cycles Waste Manage. **(9 pages)**.

Nsimbe, P.; Mendoza, H.; Wafula, S.T.; Ndejjo, R., (2018). Factors Associated with Composting of Solid Waste at Household Level in Masaka Municipality, Central Uganda. J. Environ. Public Health, 2018: 1284243 **(7 pages)**.

Pemerintah Indonesia, (2012). Peraturan Pemerintah Republik Indonesia Nomor 81 Tahun 2012 Tentang Pengelolaan Sampah Rumah Tangga dan Sampah Sejenis Sampah Rumah Tangga. Sekretariat Negara, Jakarta **(36 pages).**

Pemerintah Indonesia, (2020). Peraturan Pemerintah Republik Indonesia Nomor 27 Tahun 2020 Tentang Pengelolaan Sampah Spesifik. Sekretariat Negara, Jakarta **(59 pages).**

Pocas, F.; Selbourne, M.C., (2023). Drivers, advances, and significance of measures for effective circular food packaging. Front. Sustain. Food Syst., 7 **(11 pages).**

Rai, P.K.; Sonne, C.; Song, H.; Kim, K.H., (2022). Plastic wastes in the time of COVID-19: Their environmental hazards and implications for sustainable energy resilience and circular bio-economies. Sci. Total Environ., 858: 159880 **(15 pages)**.

Raja, K.; Bhakta, H.; Prakash, V.; Samal, B.; Bhattacharya, J., (2020). Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. Sci. Total Environ., 750: 141514 **(10 pages)**.

Roche, C.I.; Sánchez, F.V.; Gallardo, I.; Górriz, M.; Torrijos, P.; Aliaga, C.; Franco, J., (2021). Household plastic waste habits and attitudes: A pilot study in the city of Valencia. Waste Manage. Res., 39(5): 679–689 **(11 pages)**.

Russo, F.; Oreto, C.; Veropalumbo, R., (2022). Promoting resource conservation in road flexible pavement using jet grouting and plastic waste as filler. Resour. Conserv. Recycl., 187: 106633 **(15 pages).**

Salhofer, S.; Jandric, A.; Soudachanh, S.; Xuan, T.L.; Tran, T.D., (2021). Plastic recycling practices in vietnam and related hazards for health and the environment. Int. J. Environ. Res. Public Health, 18(8): 4203 **(13 pages)**.

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4).

Schmidt, S.; Laner, D., (2021). The multidimensional effects of single-use and packaging plastic strategies on German household waste management. Waste Manage., 131: 187–200 **(14 pages)**.

Shah, P.; Yang, J.Z., (2023). It Takes Two to Tango: How Ability and Morality Shape Consumers' Willingness to Refill and Reuse. Environ. Manage., **(12 pages)**.

Shams, M.; Alam, I.; Mahbub, M.S., (2021). Plastic Pollution During COVID-19: Plastic Waste Directives and Its Long-term Impact on The Environment. Environ. Adv., 5: 100119 **(11 pages)**.

Shekoohiyan, S.; Parsaee, F.; Ghayour, S., (2022). Assessment of knowledge, attitude and practice about biomedical waste management among healthcare staff of Fasa educational hospitals in COVID-19 pandemic. Case Stud. Chem. Environ. Eng., 6: 100207 **(7 pages)**.

Sidhu, N.; Pons-Buttazzo, A.; Muñoz, A.; Terroso-Saenz, F., (2021). A collaborative application for assisting the management of household plastic waste through smart bins: A case of study in the Philippines. Sensors, 21(13): 4354 **(23 pages)**.

SIPSN, (2023). Capaian kinerja pengelolaan sampah.

Ssemugabo, C.; Wafula, S.T.; Lubega, G.B.; Ndejjo, R.; Osuret, J.; Halage, A.A.; Musoke, D., (2020). Status of Household Solid Waste Management and Associated Factors in a Slum Community in Kampala, Uganda. J. Environ. Public Health, 2020: 6807630 **(10 pages)**.

Sun, Y.; Wang, D.; Li, X.; Chen, Y.; Gue, H., (2023). Public attitudes toward the whole life cycle management of plastics: A text-mining study in China. Sci. Total Environ., 859: 159981 **(10 pages).**

Trubetskaya , A.; Sholten, P.B.V.; Corredig, M., (2022). Changes towards more sustainable food packaging legislation and practices. A survey of policy makers and stakeholders in Europe. Food Packag. Shelf Life, 32: 100856 **(7 pages).**

Van R.M.L.; Nkomo, S.L.; Dube, T., (2020). The 'plastic waste era'; social perceptions towards single-use plastic consumption and impacts on the marine environment in Durban, South Africa. Appl. Geogr., 114: 102132 **(9 pages)**.

Wang, A.; Dang, S.; Luo, W.; Ji, K., (2022). Cultural consumption and knowledge, attitudes and practices regarding waste separation management in china. Int. J. Environ. Res. Public Health. 19(1): 338 **(19 pages)**.

Winton, D.; Marazzi, L.; Loiselle, S., (2022). Drivers of public plastic (mis)use — New insights from changes in single-use plastic usage during the Covid-19 pandemic. Sci. Total Environ., 849: 157672 **(10 pages)**.

Yang, Q.; Yang, S.; Jiao, Y., (2023). Assessing disposable masks consumption and littering in the post COVID-19 pandemic in China. Environ. Pollut., 334: 122190 **(7 pages).**

Zhao, S.; Zhang, J., (2023). Microplastics in soils during the COVID-19 pandemic: Sources, migration and transformations, and remediation technologies. Sci. Total Environ., 883: 163700 **(15 pages).**

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ORIGINAL RESEARCH PAPER

Development of a sustainable, green, and solar-powered filtration system for E. coli removal and greywater treatment

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ABSTRACT

BACKGROUND AND OBJECTIVES: Jordan's limited water resources have reduced daily water consumption, leading to a highly concentrated greywater production rate of 54 million cubic meters per year. The presence of nitrate ions, total dissolved solids, total suspended solids, chemical oxygen demand, and biological oxygen demand in greywater poses excellent environmental and health risks when disposed untreated. Water scarcity directly impacts water and food security and is expected to intensify at the current resources management practices. The significance of the current and predictable water shortage in the context of sustainable development and the presence of new technologies brought further attention to utilizing non-conventional water sources. Reclamation of treated wastewater, greywater, brackish, and seawater desalination is Jordan's water budget's only non-conventional water resource. This study aims to address Jordan's water scarcity crisis by developing a low-energy, solar-powered greywater filtration system using natural materials while ensuring compliance with Jordanian standards for safe agricultural applications.

METHODS: Several treatment methods have been proposed; however, most of these systems require high to medium energy levels for treatment purposes. Hence, the running cost of the system is relatively high. To address this issue, a four-stage, low-energy, green, and decentralized solar filtration system for greywater treatment has been developed, which uses natural materials available in Jordan and activated carbon to reduce organic and solids content and remove pathogens. The system also uses hot water generated by a Photovoltaic solar system to sanitize the greywater, a novel concept of approach for sanitization. This innovative system is powered entirely by solar energy and can be installed in individual homes.

FINDINGS: The results of the developed solar filtration system were very efficient in reducing turbidity, chemical oxygen demand, and Escherichia coli removal: 92, 95, and 100 percent, respectively. Furthermore, the system showed a high potential for total coliforms and Escherichia coli inactivation, reaching 4.64 and 3.15 log units, respectively. Product water meets Jordan standards, ensuring safe reuse for irrigation applications. The findings of this study highlight the satisfactory performance of the developed greywater solar filtration setup. The economic feasibility analysis demonstrates that the proposed system is economically viable and financially sound. The system's reliance on solar energy and the absence of consumables contribute to its sustainability. They are addressing sustainable practices in greywater treatment in addition to water scarcity concerns.

CONCLUSION: The treated greywater, obtained through the series of treatment steps, including solar disinfection, successfully met the Jordanian standards for safe reuse. The substantial reduction of Escherichia coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in generating pathogen-free greywater, suitable for a wide range of applications. The study concludes that the solar filtration setup consistently delivers high-quality, pathogen-free greywater, meeting stringent regulatory requirements. This innovative, sustainable system offers a viable solution to Jordan's water scarcity, introducing a new non-conventional water resource that requires no consumables (non-chemical, non-hazardous materials), thereby addressing sustainability concerns in greywater treatment.

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INTRODUCTION

Almost 94 percent of people in Jordan have access to fresh water through the public network, and 93 percent (%) have access to clean sanitation services (63% via the public sewer network and 30% via other safe means) (MWI, 2023). As a leader in the reuse of treated wastewater, 90% of wastewater produced in Jordan around 178.2 million cubic meters (m^3) annually- is treated at 32 wastewater treatment plants to ensure compliance with Jordanian irrigation and industrial reuse standards and is reused directly or indirectly in agriculture (Bdour and Hadadin, 2005). According to the most recent water budget report from the Ministry of Water and Irrigation (MWI, 2023), the available water from all resources in 2022 was 1104.8 million m^3 distributed as 30.8% surface water, 54.4% groundwater, 14.5% treated wastewater, and 0.3% sea desalinated water (Fig. 1.). Around 96% of available water are mainly used for domestic and agricultural purposes, where the municipal uses about 47.5%, irrigation uses 48.6%, and the industrial sector uses only 3.3% (WMI, 2023). The domestic water demands represent one of the most significant challenges faced by the water sector in Jordan. Water Authority of Jordan (WAJ) claimed that as the drinking water deficit remains an alarming problem due to water shortage, the exponential population growth intensifies the domestic water needs, creating inflation in the domestic water tariffs (MWI, 2023). Over the last decade, WAJ decided to increase the water charges for domestic and industrial uses to compensate for the prolonged increase in water demands accompanied by the intense water shortage. The domestic and industrial water tariffs have almost doubled over the last decade. As such, although the most significant freshwater sources are allocated to the agricultural sector (about 51-60% of the groundwater), the irrigation water tariffs also increased, at least by more than 20% (MWI, 2023; Van Den Berg and Agha Al Nimer, 2016).

Overview of the promising role of greywater

For countries with limited water resources, every droplet is very important. Jordan is considered one of the poorest countries in water availability rates according to the population-resource equation (Fig. 2). This water challenge has increased in the last few decades as a result of natural expansion as well as the influx of refugees. Hence creating a burden on the limited water resources. In other words, the water used is higher than the renewable supply (Halalsheh *et al.*, 2008). This water shortage leads to the production of large amounts of concentrated greywater. Finding alternative water resources and recycling methods is important since greywater can be collected, treated, and later used in agricultural fields (Chowdhury and Abaya, 2018). Greywater is generally defined as wastewater resulting from used water except for toilet use (fecal contamination) (Hadadin *et al.*, 2010). The composition and

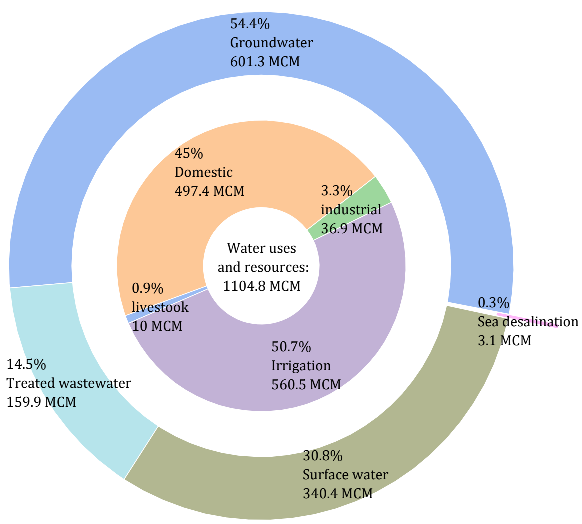

Fig. 1: Water uses and resources for 2022 (MWI, 2023)

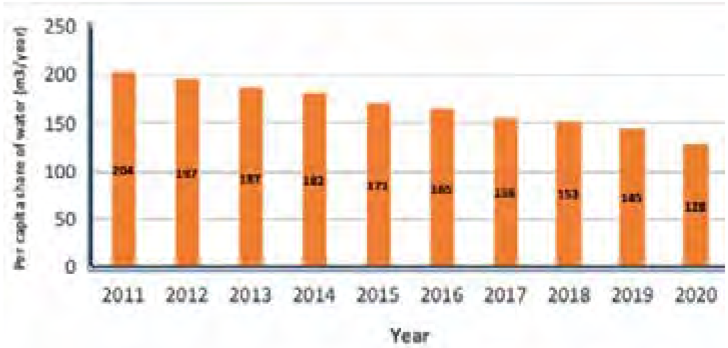

Fig. 2. Per capita share of water in (m^3/year) in Jordan for the last decade (MWI, 2023)

characteristics of greywater vary and reflect the nature of lifestyle and the variations in used water compared to discharged waste. It is acidic and has a potential of hydrogen (pH) value of 5.44 (Chowdhury and Abaya, 2018; Balasubramanya *et al.*, 2022). It is estimated that 50-80% of greywater is produced from household wastewater (Balasubramanya *et al.*, 2022; Albalawneh and Chang, 2015). In 2018, the amount of greywater produced in Jordan at the household level typically ranged from 51 to 63 Liter per person per day (L/person/day) and about 54 million m^3/ year (Al Arni *et al.*, 2022). Few studies investigated the characteristics of greywater. Ammari *et al.* (2014) reported the average values of nitrates (NO^3), total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), and biological oxygen demand (BOD) to be 104.7, 2022, 508, 1688, and 1155 parts per million (ppm), respectively. The reported characteristics were higher than the Jordanian standards (JS 893/2006) of chemical and biological characteristics for recycled greywater, indicating the need for treatment before use. Various technologies are being studied and developed for greywater treatment. Some technologies focus on biological treatment systems, including upflow anaerobic sludge blanket (UASB), membrane bioreactors (MBR), constructed wetlands (CW), and sequencing batch reactors (SBR). For example, by adding seed sludge from an anaerobic digester processing primary and secondary sludge, UASB achieved 76% biodegradability and 84% COD removal (Leong *et al.*, 2017). However, the specific conditions affecting their performance, such as greywater fractions and loading rates, need more detailed exploration to optimize their efficiency (Bani-Melhem *et al.*, 2023). Hybrid membrane bioreactors (HMBR) removal of COD, BOD_5, and total phosphorus (TP) was identical to conventional bioreactors except for ammonia (NH_3), which was slightly higher in the modified bioreactor (Palmarin and Young, 2019). Using a multistage CW showed that the system performance depends on different greywater fractions and hydraulic and organic loading rates (Magalhães Filho *et al.*, 2021). The coupling between SBR and solar photocatalytic reactor (SPCR) as a potential method to remove contaminants from greywater (organics, nutrients, and emerging contaminants (ECs)) reached 100% efficiency for the net total organic carbon (TOC) removal, and 93 % for total nitrogen (TN) removal (Priyanka *et al.*, 2022). While HMBR demonstrated similar performance to conventional bioreactors, understanding the implications of higher ammonia levels in modified bioreactors is essential for evaluating its overall effectiveness (Blanky *et al.*, 2017).

Other technologies looked into chemical treatment systems, such as granular activated carbon, coagulation (GAC), ion exchange, and photocatalytic oxidation. The study of biologically active GAC (BAC) as a recommended media for biofilters found that the Freundlich isotherm was the best fit for the equilibrium adsorption data; the adsorption kinetics were found to be best fit by the pseudo-second-order and intraparticle diffusion models. Also, intraparticle pore diffusion was rate-limited, with some mass transfer resistance due to external film diffusion at lower COD gradients (Sharaf and Liu, 2021). The assessment performance of intermittently operated saturated filters of different grain sizes using natural greywater coagulated with polyaluminium chloride (PACl) based on physicochemical and microbial parameters showed a significant reduction in turbidity, BOD, and COD

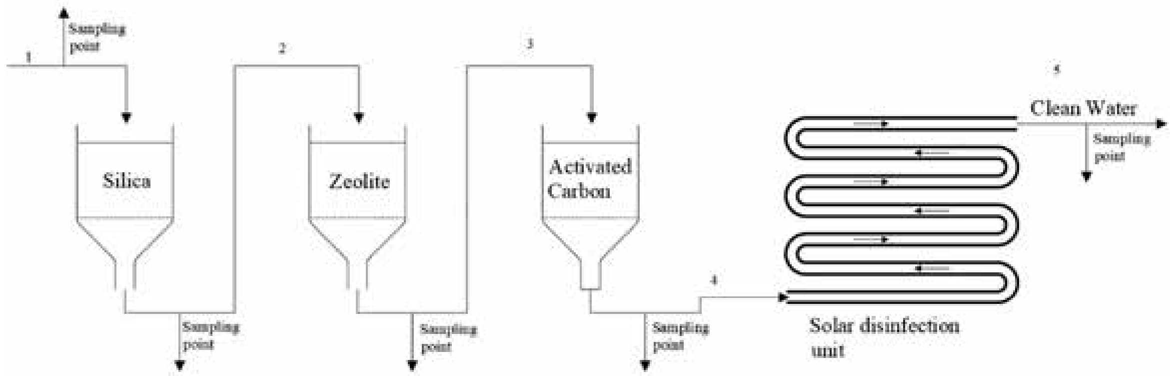

Fig. 3: Flow chart of the proposed solar filtration system (SFS)

by 94, 76, and 80%, respectively when using sand filtration after coagulation (Singh *et al.*, 2021). Spent green tea was evaluated as a potential adsorbent to remove toxic materials from greywater, such as mercury (Hg^{2+}), lead (Pb^{2+}), and cadmium (Cd^{2+}), which found the highest adsorption capacity for Hg^{2+} and Pb^{2+} ranged from 10 to 100 milligram/gram (mg/g). The adsorption efficiency at various concentrations in mono systems by the adsorbent from tea waste ranged from 99.99% to 100% for Hg^{2+} and Pb^{2+} and also from 11.11% to 18.28% for Cd^{2+} (Gameli *et al.*, 2022). Also, a submerged spiral-wound ultrafiltration (UF) membrane module for a greywater treatment system was investigated. It found that the UF membrane filtration system could maintain a permeate flux of 6 to 10 Liter per square meter per hour (L/m^2/h). TOC in the permeate can be reduced from 161 milligrams per liter (mg/L) in the influent to 28.6 mg/L, resulting in an average elimination rate of 83.4 (Li *et al.*, 2009a). It needs a discussion on the long-term performance, fouling issues, and practical considerations for large-scale implementation (Khalil and Liu, 2021). Physical treatment systems are also being studied, including membrane filtration and coarse sand and soil filtration, which was mostly followed by a disinfection step (Li *et al.*, 2009b). The effectiveness and performance of a horizontal series filter (HSF) containing different efficient adsorbents such as GAC, natural zeolite, and pumice in single and combined forms for the removal of COD, BOD5, TDS, pH, and turbidity from greywater showed that GAC outperformed zeolite as the best adsorbent for removing COD, BOD5, and TDS from greywater. However, pumice is preferable for removing turbidity (Bahrami *et al.*, 2020). It reported that the biodegradability of greywater is badly affected due to the existence of surfactants and nutrients. The standard greywater treatment methods only removed some of the amount of surfactants and nutrients. These nutrients are the best food to be consumed by bacteria such as Escherichia Coli (*E. coli*), found in greywater. Despite the efficiency of these proposed systems, these treatment systems suffer from a significant drawback as they require a high to medium level of energy for treatment purposes; hence, the system's running cost is relatively high (Waris and Ghaith, 2022). The primary aim of the current study is to design a decentralized, low-cost, and green greywater treatment system that can recycle treated water for toilet flushing, garden irrigation, and car washing purposes rather than disposing of it into the sewer.

Moreover, hot water using a photovoltaic (PV) solar system will be utilized to sanitize the greywater by elevating water temperature to a level that can kill most pathogens and microorganisms in greywater. These objectives collectively aim to advance the understanding of greywater treatment technologies, offer a practical solution with environmental and economic benefits, and provide valuable non-conventional water resources in regions facing water scarcity challenges. This study was conducted at Jordan University of Science and Technology (JUST) in 2022-2023. By addressing the aforementioned knowledge gaps, this study can ensure that the proposed greywater treatment system is innovative, sustainable, and precisely tailored to the challenges presented by Jordan's water shortage dilemma.

MATERIALS AND METHODS

The greywater treatment system designed and developed in this study is to be decentralized and standalone, allowing it to be installed at individual households, buildings, or properties. This approach provides building owners, whether residential or commercial, the flexibility to install a system tailored to their needs and reuse the treated water for different purposes. Also, the system has a low energy consumption and is driven by solar energy.

System design and development

In recent years, various natural minerals, including clay, silt, and zeolite, have significantly removed hazardous materials from water and wastewater resources. The developed system treats greywater in four stages, as shown in Fig. 3. Stages 1, 2, and 3 contain silica sand, zeolite, and activated carbon, respectively. The designed system directs water to enter each stage aforementioned from the top and exit to the next stage from the bottom. Then, the treated water is passed through solar collector tubes. The greywater will undergo several filtration stages intended to remove solids that may be present via silica sand, absorb chemicals that may be present by zeolite, and remove any residual detergents and odor that may remain in the greywater using activated carbon. The output of the third tank passed through solar collector tubes, which provide uniform heating to avoid any cold spots where pathogens may survive and overcome microbial and pathogen resistance for chemical treatment.

The solar disinfection step was introduced as thermal disinfection is probably the eldest disinfection technique (Pansonato *et al.*, 2011). The temperature of filtered greywater is increased and optimized to reach about 70 degrees Celsius (°C), which is higher than the optimal temperature for heat pasteurization of 65°C needed to kill existing pathogens in greywater (Al-Gheethi *et al.*, 2013; Khajvand *et al.*, 2022). Moreover, introducing hot air into the first three stages of the system through a specially designed opening was also tested to investigate the effect of hot air in enhancing the treatment results by sanitizing the treatment medium and water. Hot air was introduced through solar units that heated and conducted the ambient air into the tanks. In order to optimize the operating parameters, this study investigated the optimum flow rates of feed water, material characteristics, operating temperature, and contact time. The experimentation was based on the quality of the treated water and incorporated physical and chemical tests required by the Jordanian standards of water (JS 893/2006) (Ammari *et al.*, 2014). Fig. 4 shows the greywater system that has been designed and used in this study, which consists of the three tanks, while Fig. 5 shows the solar panels used for hot air and the disinfection unit.

To determine the optimum contact time for sanitizing greywater, several factors were considered in this study, including initial pathogen concentration, initial water temperature, and desired level of disinfection. Commonly, at higher temperatures, the required contact time is shorter. This study investigated contact time intervals, namely, 2 minutes, 4 minutes, and 6 minutes, to determine the sufficient level needed to achieve the desired reduction in fecal coliform bacteria that meets Jordan Standards for recycling reclaimed domestic wastewater (JS 893/2006). Herein, more than hot water treatment is required for the complete disinfection of all types of pathogens, and other treatment techniques may need to be combined to achieve the desired level of disinfection.

Experimental procedures

One milestone aspect of this study was the optimization of various parameters of the treatment process, such as the size of silica sand particles used in the first stage of treatment. Initially, a 400 micrometer (µm) silica sand was used, but this particle size was unsuitable as it blocked the porosity and clogged the treatment tank due to the small size. Changing the size to around 1 millimeter (mm) showed a better performance of the treatment tank. Table 1 shows the grain size distribution of the various filtration mediums used in this experiment. For silica, most of the medium falls within the range of greater than 600 µm and less than 1.8 mm, accounting for 86% of the total. A tiny portion, only 0.90%, lies within the range of greater than 1.8 mm and less than 2 mm. The remaining 13.10% of the silica medium has a diameter smaller than 600 µm.

A total of 2400 liters (L) of greywater from domestic household showers and bathroom sinks were treated using the proposed system. The water was treated

Fig. 4: Developed greywater filtration system

Fig. 5: Solar panels used for hot air and the disinfection unit

with and without the introduction of hot air. It is worth noting that no synthetic greywater was used in this study. The tests were conducted on different days due to the limited daily greywater collection and unsuitable weather conditions. Greywater from the bathroom sink and showers were mixed in a tank and conveyed to the tanks according to the previous description. Samples of water from the mixture tank and out of each tank were collected to conduct different physical, biological, and chemical tests; locations of sampling points are shown in Fig. 3. A total of 24 greywater samples were collected from the influents and effluents of the SFS stages, and stored at room temperature for a maximum of three days. The collected samples were analyzed for pH, electrical conductivity, turbidity, BOD, COD, TOC, density, E. coli, and total coliforms. The majority of the tests were conducted at the WAJ laboratories.

The greywater system designed in this study operates as a decentralized and standalone unit, providing adaptability for individual installation in wide settings. The four-stage treatment process incorporates silica sand, zeolite, and activated carbon to eliminate solid contaminants effectively, absorb chemicals, and neutralize residual detergents and odor. Solar collector tubes and the introduction of hot air contribute to thermal disinfection, optimizing pathogen elimination (Samimi and Moghadam, 2024). Experimental procedures involved an essential optimization phase, determining factors like silica

Table 1: The grain size distribution of the various filtration mediums used in this experiment.

Silica		Zeolite		Granular activated Carbon	
600 µm -1.8 mm	86%	600 µm -1mm	19%	300 µm - 600 µm	2%
1.8 mm-2 mm	0.90%	300 µm - 600 µm	24%	600 µm - 1mm	98%
<600 µm	13.10%	1 mm -1.4 mm	57		

Table 2: Average measurements for treatment with and without hot air

Measured parameter	With hot air				Without hot air			
	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank
pH	7.29	7.5	7.6	8.01	7.22	7.3	7.5	7.81
TDS	428	429	442	448	593	436	448	488
Turbidity	62.6	25.8	4.8	4.4	77.2	35.2	7.9	4.5

sand particle size, contact time, and the impact of hot air introduction. Notably, optimizing the treatment process parameters, such as the size of silica sand particles, was undertaken to enhance overall system performance. The experiments used 2400 liters of natural domestic greywater from showers and bathroom sinks. Samples were collected at various stages, and a comprehensive set of physical, chemical, and biological tests were performed to evaluate the system's efficiency. The grain size distribution of filtration media was carefully considered, with adjustments made for optimal performance. The methodology ensured a robust investigation, addressing specific challenges identified in greywater treatment.

RESULTS AND DISCUSSION

Sand filtration media

Basic tests were made on the site where the treatment system is located. Each tank, including the mixture tank, TDS, pH, and turbidity, were measured and recorded for 18 test runs. The readings of the mixture tank were also taken as a reference to investigate the efficiency of the treatment process. Table 2 lists the average measurements for the treatment of 2400 L with and without the introduction of hot air for each filtration stage. The changes in measurements through the treatment process suggest that the medium nature of filtration tanks could cause such changes, such as an increase in pH values throughout the stages and a significant decrease in turbidity. No change was seen in TDS values, suggesting that extra chemical treatment might be needed to decrease these readings. At this stage, no apparent effect of using hot air was seen as the trend of the measurements did not differ; theoretically, there is no role of hot air in these measurements.

According to the Jordanian standards for treated greywater, treated wastewater must have a pH value between 6 and 9, TDS up to 2000 mg/L, turbidity up to 5 nm, and according to the results presented in Table 2, the treated water meets these standards. It can be used for various usages, such as irrigation and toilet flushing. Another set of tests used for qualifying greywater includes measuring concentrations of some heavy metals in the treated water. The same samples were collected and tested on Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) at JUST. Table 3 lists the average results of some heavy metal concentrations versus Jordanian standards. The results are for an average of 2400 L of greywater treatment. The results in Table 3 show that the water in different tanks matches the standard in terms of heavy metal concentration. It is also worth mentioning that the water in the mixture tank meets the standard; the medium-used tanks do not affect the heavy metal concentration. However, some concentrations increased at certain tanks but were still within the limits of the Jordanian standards. Hot air usage does not show a significant effect.

Chemical and biological tests were conducted in the quality laboratories at the Water and Irrigation Ministry. A total of 2400 L were treated, and samples were collected and sent to the laboratories in three batches. Table 4 lists the average results of biological and chemical tests versus the Jordanian standards; the tests include measurements for BOD, COD, E.

Table 3: The average results of some heavy metals concentration versus Jordanian standards

	With hot air (mg/L)				Without hot air (mg/L)				JS 893/2006
Heavy metals	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Standard value (mg/L)
Li	0	0	0	0	0	0	0	0	2.5
Al	0.45	0.4	0.72	0.51	0.52	4	0.46	0.36	5
V	0	0	0	0	0	0.01	0	0	0.1
Cr	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.1
Fe	0.28	0.12	0.44	0.49	0.21	2.75	0.23	0.37	5
Mn	0	0	0.01	0.01	0	0.06	0	0	0.2
Co	0	0	0	0	0	0	0	0	0.05
Ni	0.01	0.01	0.03	0.01	0.01	0.04	0.01	0.01	0.2
Cu	0.01	0.01	0.02	0.07	0.01	0.03	0.01	0.03	0.2
Zn	1.21	1.55	1.49	2	1.54	1.63	1.48	1.68	2
Cd	0	0	0	0	0	0	0	0	0.01
Pb	0.03	0.01	0.15	0.23	0.02	0.05	0.03	0.07	5

coli, and acrylonitrile-butadiene-styrene (ABS). The results in Table 4 show that the treated water from the system can be used for irrigation but not for toilet flushing. Also, using hot air does not improve the result of treated water. In fact, hot air has a negative effect on *E. coli* results as this type of bacteria is an aerobic bacterium, so it will reproduce in a medium that contains air and high temperature. However, the treated water using hot air can still be used for irrigation. This summarized all tests that have been conducted for the greywater treatment system. All results confirm the standards, so the system that has been used can be efficient in treating greywater to save the waste of water that can be used for other purposes, especially for irrigation.

Solar disinfection

The results presented in Table 5 demonstrate the effect of each treatment phase on COD, BOD, total coliform, and *E. coli levels* in the treated greywater. The treatment process involved passing the filtered greywater through a series of treatment phases, including silica sand, zeolite, carbon, and solar tubes. The initial concentration of Escherichia coli was 49,000, the most probable number per 100 milliliters (MPN/100mL). No effect was seen on E. coli concentration in the first two stages of filtration (Silica sand and Zeolite tanks), which remained consistent at a concentration of 49,000 MPN/100mL. However, a significant reduction to 1400 MPN/100mL was measured after passing through the Carbon tank, reaching a 0.54 log units *E. coli* inactivation. This indicates that the carbon filtration process effectively removed a substantial portion of the E. coli present in the greywater. The solar disinfection treatment unit remarkably impacted the E. coli content, reducing it to 0 MPN/100mL. Results indicate that the solar disinfection unit was highly effective in removing E. coli from the greywater, reaching a 3.15 log unit E. coli inactivation, comparing the results of the microbial removal of SFS with other systems investigated in previous studies, such as stand-alone sand filtration, rotating biological contactor followed by sand filtration, and a membrane bioreactor equipped with ultrafiltration membranes (Friedler *et al.,* 2006). Both rotating biological contactors, followed by sand filtration and membrane bioreactor, exhibited substantial microbial removal, with 2.1 and 3.6 logs removal (Friedler et al., 2006), while the SFS system achieved a 3.15 log units E. coli inactivation.

Similarly, the initial concentration of total coliforms was 16,000,000 MPN/100 *mL*. The subsequent treatment steps in the silica sand and zeolite tanks decreased total coliform concentration to 5,400,000 MPN/100mL (0.47 log units' total coliforms inactivation). The value was significantly reduced to 79,000 MPN/100mL (1.83 log units' total coliforms inactivation) after passing through the carbon tank, as illustrated in Fig. 6.

Remarkably, the solar treatment unit brought the total coliform count to a level lower than 1.8 MPN/100 *mL,* reaching 4.64 log units' total coliform inactivation. This indicates that the solar disinfection process reduced the total coliform concentration and met the specified limit, suggesting that the greywater was effectively treated to remove coliform bacteria. In terms of organic pollutants, the levels of BOD and

Table 4: The average results of biological and chemical tests versus the Jordanian standards

Test	With hot air (mg/L)				Without hot air (mg/L)				JS 893/2006 Standard value
	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	
BOD (mg/L)	26	28	30	14	27	29	29	13	60 (mg/L) (Irrigation) 10 (mg/L) (Toilet flushing)
COD (mg/L)	456	416	137	22	330	262	124	14	120 (mg/L) (Irrigation) 20 (mg/L) (Toilet flushing)
E-coli (MPN/100mL)	22,000	110,000	17,000	4,900	14,000	1,100	700	700	10^4 (MPN/100mL) (Irrigation)10 ((MPN/100mL) (Toilet flushing)
ABS (mg/L)	1.1	1.2	1.3	0.5	1.2	1.3	1.3	1	25 (mg/L)

Table 5: Effect of each treatment step on COD, BOD, total coliform, and Escherichia Coli

Measured parameter	Silica sand tank	Zeolite tank	Carbon tank	Solar tube	Unit
Escherichia coli	49,000	49,000	1400	0	MPN/100mL
Total Coliforms	16,000,000	5,400,000	79,000	<1.8	MPN/100mL
BOD	24	22	11	12	mg/L
COD	545	56	29	19	mg/L

COD were progressively reduced throughout the treatment process. The BOD concentration decreased from 24 mg/L in the untreated greywater to 11 mg/L after passing through the carbon tank, and the COD concentration decreased from 545 mg/L to 29 mg/L in the same treatment step. The solar tube treatment resulted in a slight increase in BOD (12 mg/L) and a further decrease in COD (19 mg/L), as shown in Fig. 7.

A one-way analysis of variance (ANOVA) (Samimi *et al.,* 2023) was conducted to assess the statistical differences among the means of each treatment step for the parameters of interest, including E. coli, Total coliform, BOD, and COD. The results revealed statistically significant mean differences for all analyzed parameters ($p < 0.05$) (Samimi and Nouri, 2023). These results indicate that the overall efficiency of greywater SFS was sufficient. Treated greywater obtained after the various treatment steps, including the solar disinfection process, met the Jordanian standards for safe reuse. Reducing E. coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in providing pathogen-free greywater suitable for various applications. The solar-equipped filtration unit succeeded in greywater treatment, particularly in turbidity, chemical oxygen demand (COD), and Escherichia coli (E. coli) removal. A comparative analysis of treatment efficiency with and without the solar system provides valuable insights into the benefits of solar disinfection. Table 5 presents the effect of each treatment step on COD, BOD, total coliform, and E. coli in the treated greywater. Solar disinfection was highly effective, reducing E. coli concentration to 0 MPN/100mL, demonstrating a 3.15 log units E. coli inactivation. The solar treatment unit also brought the total coliform count to a level lower than 1.8 MPN/100 mL, reaching a 4.64 log unit total coliform inactivation. These results underscore the success of the solar disinfection process in achieving pathogen-free greywater, making it suitable for various applications. The solar-equipped filtration unit meets water quality standards and demonstrates enhanced efficiency in pathogen removal, affirming its suitability for safe water reuse in various contexts.

SFS lifecycle cost analysis (LCCA)

The LCCA of the SFS includes four major items as illustrated in Table 6: Initial investment 1) which include storage tanks, pumps, solar panels, drainpipes, pipe fittings, filter media, and electrical control devices; 2) Operating and maintenance costs (OMC) which includes costs of filer medium replacement every ten months and cost of regular

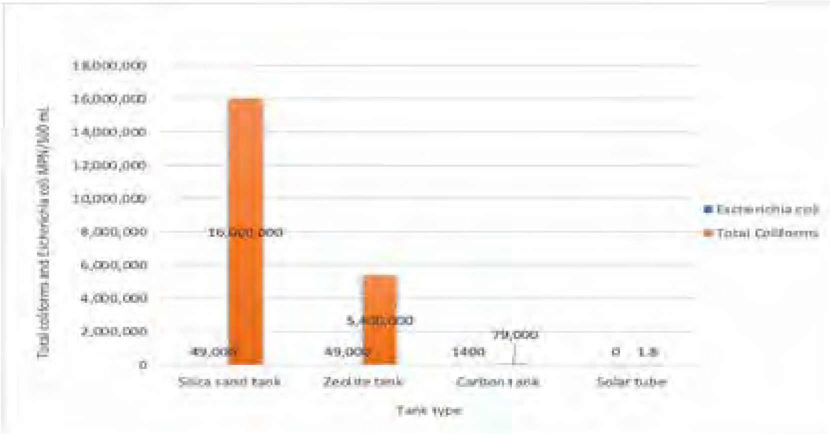

Fig. 6: Total coliforms and Escherichia coli removal efficiencies across different tanks

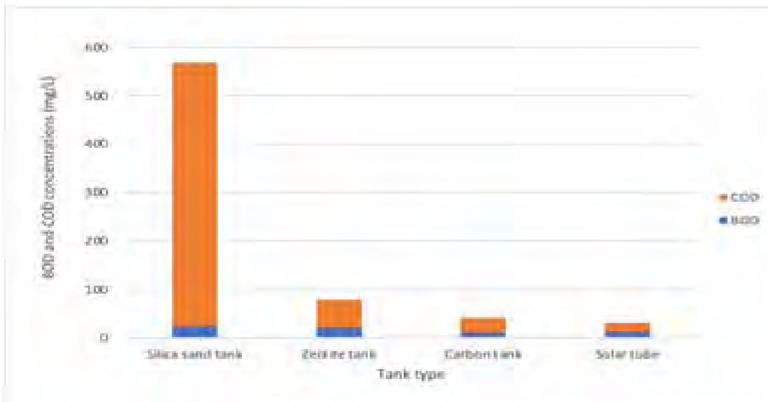

Fig. 7: BOD and COD removal efficiencies across different tanks

cleaning of the solar panel, and fittings and parts replacements; 3) Assuming the revenues and savings (RS) of using SFS water will approximately save 40% of the water utility bill which is 17.5 US Dollars (USD) per month (210 USD) yearly per dwelling unit; 4) Resale or Salvage value; assuming that SFS needs replacements approximately every 15 years and costs 340 USD. To perform financial calculations and evaluate the economic viability of the proposed system over its entire lifespan, Table 6 shows the values used in the economic feasibility calculations.

In this study, the net present value (NPV) has been calculated to investigate the LCCA with a minimum acceptable rate of return (MARR) of a minimum of 3% (Juan *et al.*, 2016). This analysis used three leading investments using Eq. 1 (Bdour *et al.*, 2023).

With Net Present Value (NPV)

$$NPV=\sum\left(\frac{RS-OMC}{(1+DR)^{2}})-\mathrm{II}+\frac{SV}{(1+DR)^{2}}\right) \tag{1}$$

With Payback Period (PP), using Eq. 2 (Bdour *et al.*, 2023).

$$PP=\frac{II}{\sum(RS-OMC)} \tag{2}$$

With Benefit Cost Ratio (BCR), using Eq. 3 (Bdour *et al.*, 2023).

$$BCR=\frac{\sum RS}{II+\sum OMC} \tag{3}$$

Where; II: Initial investment of SFS system

Table 6: SFS Lifecycle cost analysis parameters

Parameter	Value
Initial Investment (II)	USD 850
Operating and Maintenance Costs (OMC) per year	USD 120
Revenues and Savings (RS) per year	USD 210
Lifecycle Duration (LD)	15 years
Discount Rate (DR)	10%
Resale Value (SV)	USD 340

OMC: Operating and Maintenance cost of SFS per year.

RS: Revenues and Savings per year, representing the difference between water bills with and without the SFS system.

LD: Lifecycle Duration, which indicates the expected operational lifespan of the setup.

DR: Discount Rate, which accounts for the time value of money.

SV: Resale Value or Salvage Value represents the potential value that can be recovered if the system is sold.

In this study, OMCs were considered part of the LCCA, as outlined in Table 6. The OMC includes the cost of filter medium replacement every ten months, regular solar panel cleaning, fittings, and parts replacements. The frequency of maintenance is designed to ensure optimal and sustained system performance. The 10-month interval for filter medium replacement is based on empirical observations and aims to address any potential decrease in filtration efficiency over time. Regular cleaning of the solar panel is essential to maintain its effectiveness in harnessing solar energy for disinfection. Table 7 shows the economic feasibility analysis of the developed SFS. These results demonstrate that the SFS system is economically viable and financially sound. The positive NPV, high initial rate of return (IRR), relatively short PP, and a BCR greater than one suggest that investment in the developed system is favorable. Furthermore, this system will be attractive to owners and households of dwelling units due to its profitability; buying it will allow them to treat and reuse a good portion of the water used for showers and toilets. This treated greywater can be used safely for irrigation without threatening their health and environment. Although the system's revenue is vital, applying this system will ultimately help lessen the water shortage in Jordan by introducing a new non-conventional water resource. Also, bearing in mind that the developed system entails no consumables (non-chemical, non-hazardous materials) that work as a standalone system to address the sustainability of greywater treatment.

According to a study by Tabieh *et al*. (2022), it was estimated that the average value to produce one cubic meter of domestic water in Jordan is 2.4 USD. However, in 2023, the government recently increased the water tariff for the domestic sector, which showed the highest water unit prices. It has been assessed that water bills for household consumers will rise by 10 USD for consumption over 73 cubic meters (MWI, 2023). Comparing this cost with other countries worldwide, the cost in the United States is 0.75 USD, Japan 1.5 USD, and Germany 3.05 USD (Varady *et al.*, 2022). Previous studies have shown that water scarcity directly impacts water and food security and is expected to intensify at the current resources management practices. Jordan's resources are being unsustainably utilized to compensate for the population needs in the supply-demand chain (Belda González, 2018). As illustrated in Figs. 8 and 9, the intensifying pressure on the country's resources, accompanied by a drastic increase in the water and food demands, is also threatening the sustainability of the energy sector in Jordan since it imports about 94% of its fossil fuel resources. This has indirectly contributed to the high electricity tariffs in Jordan.

The significance of the current and predictable water shortage in the context of sustainable development and the presence of new technologies brought further attention to utilizing non-conventional water sources (Aznar-Sánchez *et al.*, 2018; Moghadam and Samimi, 2022). Significant non-conventional resources include treated wastewater and brackish water desalination. The reclamation of the treated wastewater, brackish, and seawater desalination is the only non-conventional water resource in Jordan's water budget. Treated wastewater is primarily used for irrigation (98.4%), with a tiny amount used in the industry (1.6%). Most treated wastewater comes

Table 7: Results of SFS economic feasibility investigations

Parameter	Value
NPV	1,947 $US
IRR (NPV=0)	22.97%
PP	≈ 3.18 years
BCR	≈ 2.07

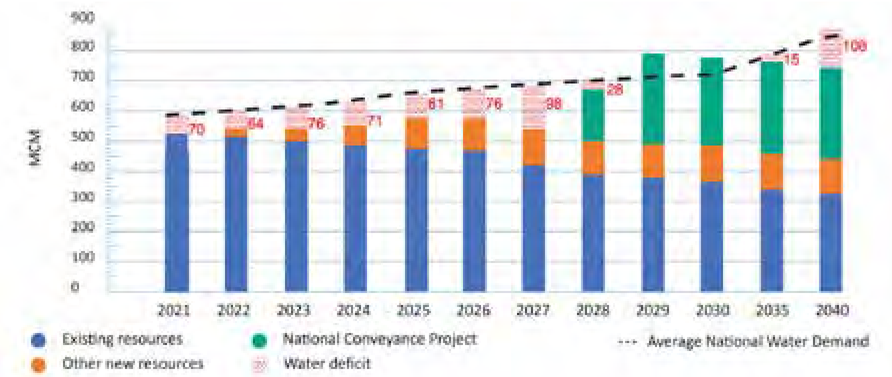

Fig. 8: Demand and supply projections for the domestic sector in Jordan (MWI, 2023)

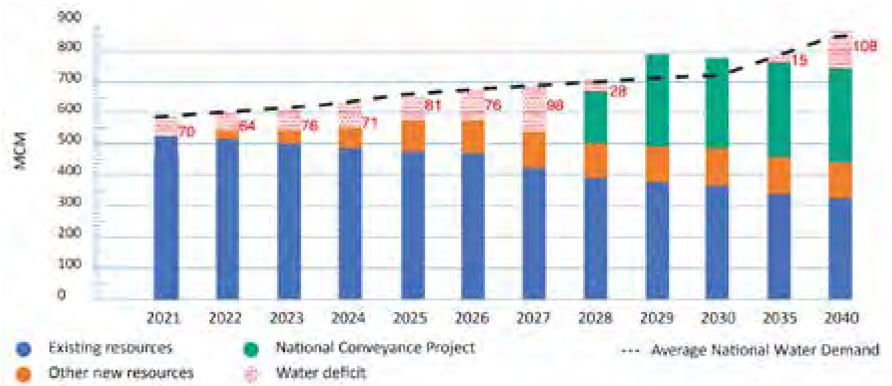

Fig. 9: Agricultural supply and demand projections in Jordan (MWI, 2023)

from wastewater treatment facilities registered in the Jordan Valley (71.3%). Because of the small coastal area in Jordan, seawater desalination has been considered on a limited scale (0.3%) as a source. This indicates that introducing a new non-conventional water resource and reducing the associated costs per cubic meter for domestic water utilization is essential in Jordan. The illustrated claim proves the outstanding economic performance attained with SFS that was primarily implemented to reduce and conserve the domestic demands of individuals. The empirical results obtained from the SFS provide valuable insights into its efficiency in treating greywater and removing contaminants, particularly E. coli. These results can be linked to previous studies, shedding light on the system's performance compared to traditional water treatment methods and its contributions to environmental sustainability. The results of E. coli removal indicate a significant reduction in E. coli concentration throughout treatment. The carbon tank achieved a 0.54 log unit of E. coli inactivation, and the solar disinfection unit further reduced it to 0 MPN/100 mL, indicating a 3.15 log unit of E. coli inactivation. This aligns with the literature emphasizing the importance of effective E. coli removal to ensure safe water reuse (Priyanka *et al.,* 2022). Also, the study monitors various parameters during the greywater treatment, including pH, TDS, turbidity, heavy metal concentrations, BOD, COD, and E. coli. The results demonstrate that the treated water meets Jordanian standards for safe reuse, supporting literature on the necessity of adhering to water quality standards in treated wastewater (Waris and Ghaith, 2022). Moreover, the SFS contributes to environmental sustainability in several ways. The use of solar energy for water treatment aligns with the global push for renewable energy adoption. The system employs natural filtration media, avoiding the need for chemical treatments and reducing the environmental impact associated with traditional water treatment methods. The decentralization of the system further minimizes the reliance on centralized infrastructure. LCCA provides insights into the economic viability of the SFS. The NPV, high IRR, short PP, and a BCR greater than 1 suggest that the SFS investment is favorable and proves a superior performance compared with other treatment technologies (Singh *et al.,* 2021).

CONCLUSION

This study introduces a novel four-stage solar filtration system for treating greywater. The system effectively reduces organic and solid content by utilizing natural materials and activated carbon and removes E. coli pathogens. It introduces a pioneering approach to greywater treatment, integrating natural filtration media and solar disinfection for efficient and sustainable contaminant removal. This novel system contributes a unique combination of renewable energy reliance and eco-friendly design, setting it apart as a groundbreaking solution in the realm of water treatment technologies. The developed system demonstrates impressive efficiency in turbidity, COD, and E. coli removal, achieving 92%, 95%, and 100%, respectively. Additionally, it exhibits substantial potential for inactivating total coliforms and E. coli, making the treated water suitable for safe reuse in irrigation applications. The combination of sand filtration and solar disinfection presents a highly favorable and environmentally conscious approach to greywater treatment. This green decentralized system utilizes natural treatment processes to produce high-quality water that can be effectively utilized in various fields, with a particular emphasis on irrigation purposes. This combination's economical and environmentally friendly nature makes it suitable for implementation by individual homeowners as well as commercial buildings, hotels, universities, and hospitals. Moreover, in regions like Jordan, where water resources are limited, adopting such a green decentralized system can significantly contribute to environmental preservation by conserving precious freshwater resources. The findings of this study highlight the satisfactory performance of the developed greywater SFS. The treated greywater, obtained through the series of treatment steps, including solar disinfection, successfully met the Jordanian standards for safe reuse. The substantial reduction of E. coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in generating pathogen-free greywater, suitable for a wide range of applications. These findings affirm the capability of the solar filtration setup to deliver high-quality treated greywater that meets stringent regulatory requirements consistently. Additionally, the economic feasibility analysis underscores the viability and financial soundness of the SFS system. Its reliance on solar energy for operation and the absence of consumables contribute to its sustainability. This addresses water scarcity concerns and aligns with sustainable practices in greywater treatment. The study's findings have significant implications for Jordan's water management. The solar filtration system offers a promising non-conventional water resource by consistently producing high-quality treated greywater that meets regulatory standards. Implementing this system has the potential to alleviate water shortages, providing a valuable contribution to sustainable water use in the region. This study adds scientific value by comprehensively investigating a novel four-stage solar filtration system for greywater treatment. The systematic evaluation of its efficiency in removing contaminants, particularly E. coli, coupled with economic feasibility analysis, contributes valuable insights to sustainable water treatment. Integrating natural materials, activated carbon, and solar disinfection showcases innovative solutions, advancing our understanding of eco-friendly technologies for decentralized water reuse systems.

AUTHOR CONTRIBUTIONS

R. Abdallat performed the research experimentation and interpretation of the results and wrote the manuscript; A. Bdour supervised the work and concept formulation and wrote the manuscript. A. Abuhaifa did the experimental work, sampling, and prototype manufacturing; F. Alrawash interpreted data and prepared all the tables and figures. L. Almakhadmah collected references, prepared the manuscript, and organized the text. S. Hazaimeh did the statistical analysis and paper editing.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	percentage
μm	micrometer
ABS	acrylonitrile-butadiene-styrene
ANOVA	Analysis of variance
BAC	Biologically active granular activated carbon
BCR	Benefit Cost Ratio
BOD	Biological oxygen demand
COD	Chemical oxygen demand
CW	Constructed wetland
Cd^{2+}	Cadmium
^{o}C	Degree Celsius
DR	Discount rate
ECs	Emerging contaminants
E. coli	Escherichia Coli
GAC	Granular activated carbon
HSF	Horizontal series filter
Hg^{2+}	Mercury
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
II	Initial investment
IRR	Initial rate of return
L	Liter
LCCA	Lifecycle cost analysis
LD	Lifecycle Duration
L/person/day	Liter per person per day
L/m/h	Liter per meter per hour
MARR	minimum acceptable rate of return
MBR	Membrane bioreactor
mm	millimeter
MPN	Most probable number
m^3	Cubic meter
mg/g	Milligram per gram
mg/L	Milligram per liter
NPV	Net Present Value
NH_3	Ammonia
NO^{-3}	Nitrates
OMC	Operating and maintenance costs
PACl	polyaluminium chloride
pH	Potential of hydrogen
PP	Payback Period
ppm	Parts per million
PV	photovoltaic
Pb^{2+}	Lead
RS	revenues and savings
SBR	sequencing batch reactor
SFS	Solar filtration system
SPCR	solar photocatalytic reactor
SV	Resale Value

TDS	total dissolved solids
TN	Total Nitrogen
TOC	Total Organic Carbon
TSS	Total suspended solids
UASB	upflow anaerobic sludge blanket
USD	US Dollars
IF	ultrafiltration
WAJ	Water Authority of Jordan

REFERENCES

Al Arni, S.; Elwaheidi, M.; Salih, A.A.; Ghernaout, D.; Matouq, M., (2022). Greywater reuses an assessment of the Jordanian experience in rural communities. Water Sci. Technol., 85(6): 1952-1963 (**12 pages**).

Albalawneh, A.; Chang, T.K., (2015). Review of the greywater and proposed greywater recycling scheme for agricultural irrigation reuses. Int. J. Res. Granthaalayah. *3*(12): 16-35 (**20 pages**).

AL-Gheethi, A.A.; Ismail, N.; Lalung, J.; Talib, A.; Kadir, M.O.A., (2013). Reduced fecal indicators and eliminated pathogens from sewage-treated effluents by heat treatment. Caspian J. Appl. Sci. Res., 2(2): 39–55 (**17 pages**).

Ammari, T.G.; Al-Zu'bi, Y.; Al-Balawneh, A.; Tahhan, R.; Al-Dabbas, M.; Ta'any, R.A.; Abu-Harb, R., (2014). An evaluation of the re-circulated vertical flow bioreactor to recycle rural greywater for irrigation under arid Mediterranean bio climate. Ecol. Eng., 70: 16–24 (**9 pages**).

Aznar-Sánchez, J.A.; Belmonte-Ureña, L.J.; Velasco-Muñoz, J.F.; Manzano-Agugliaro, F., (2018). Economic analysis of sustainable water use: A Review of worldwide research. J. Cleaner. Prod., 198, 1120-1132 (**13 pages**).

Bahrami, M.; Amiri, M.J.; Badkubi, M., (2020). Application of horizontal series filtration in greywater

Treatment: a semi-industrial study. Australas. J. Water Resour. 24(2): 236-247 (**12 pages**).

Balasubramanya, S.; Stifel, D.; McDonnell, R., (2022). Water shortages, irrigation frequency, and preference for technologies and agricultural services: The case Jordan. Irrig. Drain., 71(2): 437-451 (**15 pages**).

Bani-Melhem, K.; Elektorowicz, M.; Tawalbeh, M.; Al Bsoul, A.; El Gendy, A.; Kamyab, H.; Yusuf, M. (2023). Integrating electrocoagulation process with submerged membrane bioreactor for wastewater treatment under low voltage gradients. Chemosphere. PMID: 37536541.

Bdour, A.; Hadadin, N., (2005). Potentials and limitations of wastewater reuse in rural areas in

Jordan: The Reuse options in the Jordan Valley. J. Agron., 4(4): 315-322 (**8 pages**).

Bdour, A.; Hejab, A.; Almakhadmah, L.; Hawwa, M., (2023). Management strategies for the efficient energy production of brackish water desalination to ensure reliability, cost reduction, and sustainability. Global J. Environ. Sci. Manage., 9(SI): 173-192 **(20 pages).**

Belda Gonzalez, A., (2018). The Water-energy-agriculture nexus in Jordan: A case study on As-Samra wastewater treatment plant in the lower Jordan river basin. Master of Science Thesis KTH School of Industrial Engineering and Management Energy Technology TRITA-ITM-EX 2018: 588 Division of Energy Systems Analysis SE-100 44 Stockholm (**108 pages**).

Blanky, M.; Sharaby, Y.; Rodríguez-Martínez, S.; Halpern, M.; Friedler, E., (2017). Greywater assessment of the health risk induced by Legionella pneumophila. Water Res., 125: 410-417 (**8 pages**).

Chowdhury, R.K.; Abaya, JS (2018). An experimental study of greywater irrigated green roof systems in an arid climate. J. Water Manage. Model., 26(C437): 1–10 (**10 pages**).

Friedler, E.; Kovalio, R.; Ben-Zvi, A. (2006). Comparative study of the microbial quality of greywater treated by three on-site treatment systems. Environ. Tech., 27(6): 653-663 **(11 pages).**

Gameli, B.H.R.; Duwiejuah, A.B.; Bawa,A., (2022). Adsorption of toxic metals from greywater using low-cost spent green tea as a novel adsorbent. Sci. Afr., 17: e01296 (**9 pages**).

Hadadin, N.; Qaqish, M.; Akawwi, E.; Bdour, A., (2010). Water shortage in Jordan-Sustainable solutions. Desalination. 250(1): 197–202 (**6 Pages**).

Halalsheh, M.; Dalahmeh, S.; Sayed, M.; Suleiman, W.; Shareef, M.; Mansour, M.; Safi, M., (2008). Grey water characteristics and treatment options for rural areas in Jordan. Bioresour. Technol., 99(14): 6635–6641 (**7 Pages**).

Juan Y-K; Chen Y; Lin J-M., (2016). Greywater reuse system design and economic analysis for residential buildings in Taiwan. Water. 8(11): 546 (**11 pages**).

Khajvand, M.; Mostafazadeh, A.K.; Drogui, P.; Tyagi, R.D.; Brien, E., (2022). Greywater characteristics, impacts, treatment, and reclamation using adsorption processes towards the circular economy. Environ. Sci. Pollut. Res., 29: 10966–11003 (**38 pages**).

Khalil, M.; Liu, Y., (2021). Greywater biodegradability and biological treatment technologies: A critical review. Int. Biodeterior. Biodegrad. 161, 105211 (**13 pages**).

Leong, J.Y.C.; Oh, K.S.; Poh, P.E.; Chong, M.N., (2017). Prospects of hybrid rainwater-greywater decentralised system for water recycling and reuse: A review. J. Cleaner Prod., 142:3014-3027 (**14 pages**).

Li, F.; Gulyas, H.; Wichmann K.; Otterpohl, R., (2009a). Treatment of household grey water with
a UF membrane filtration system. Desalin. Water Treat., 5(1-3): 275-282 (**14 pages**).

Li, F.; Gulyas, H.; Wichmann K.; Otterpohl, R., (2009b). Review of the technological approaches for grey water treatment and reuse. Sci. Total Environ., 407(11): 3439 - 3449 (**11 pages**).

Magalhães Filho, F.J.; de Souza Filho, J.C.; Paulo, P.L., (2021). Multistage constructed wetland treating greywater under tropical conditions: Performance, operation, and maintenance. Recycling. 6(4): 63 (**16 pages**).

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 (**8 pages**).

MWI, (2023). National Water Strategy Year 2023-2040 in Jordan: Ministry of Water and Irrigation. (**31 pages**).

Palmarin, M.J.; Young, S. (2019). Comparison of the treatment performance of a hybrid and conventional membrane bioreactor for greywater reclamation. J. Water Process Eng., 28: 54–59 (**6 pages**).

Pansonato, N.; Afonso, M.V.G.; Salles, C.A.; Boncz, M.Á.; Paulo, P.L., (2011). Solar disinfection for the post-treatment of greywater by means of a continuous flow reactor. Water Sci. Technol., 64(5): 1178-1185 (**8 pages**).

Priyanka, K.; Remya, N.; Behera, M., (2022). Sequential biological and solar photocatalytic treatment system for greywater treatment. Water Sci. Technol., 86(3): 584-595 (**12 pages**).

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 (**7 pages**).

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 (**10 pages**).

Samimi, M.; Moghadam, H., (2024). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustain. Energy Rev., 190: 113969 (**10 pages**).

Sharaf, A., Liu, Y., (2021). Mechanisms and kinetics of greywater treatment using biologically active granular activated carbon. Chemosphere. 263: 128113 (**8 pages**).

Singh, S.; Ahammed, M.M.; Shaikh, I.N., (2021). Combined coagulation and intermittent sand filtration for on-site treatment of greywater. IOP Conf. Ser.: Mater. Sci. Eng., 1114(2021): 012031 (**8 pages**).

Tabieh, M.A.; Al-Karablieh, E.K.; Salman, A.Z.; Al-Assaf, A.; Majdalawi, M.E.; Qtaishat, T.H., (2022). An estimate of the economic value of domestic water services: a case study in Jordan. Acad. Strat. Manag. J., 21(S6):1-14 (**14 pages**).

Varady, R.G.; Albrecht, T.R.; Gerlak, A.K.; Haverland, A.C., (2022). Global water initiatives redux: A fresh look at the world of water. Water. 14(19): 3093 (**41 pages**).

Van Den Berg, C.; Agha Al Nimer, S.KH., (2016). The cost of irrigation water in the Jordan Valley. The World Bank.

Waris, A.; Ghaith, FA, (2022). Design of solar-powered greywater treatment unit for residential applications. Proceedings of the ASME 2022 Power Conference. Pittsburgh, Pennsylvania, USA. July 18–19, 2022. V001T07A004. ASME.

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CASE STUDY

Valuation of urban green open space using the Hedonic price model

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ABSTRACT

BACKGROUND AND OBJECTIVES: Urban green infrastructure, specifically green open spaces, is becoming increasingly significant in rapidly urbanizing areas. These spaces offer environmental, social, and economic advantages to urban ecosystems, thereby increasing community health and well-being. However, their economic value is often overlooked in urban planning. This study aims to conduct an economic valuation of green spaces by introducing the hedonic price model to equip decision-makers with a thorough and informed perspective.
METHODS: A questionnaire created through Google Forms was distributed through a social media survey conducted from March to April 2021. The data collected from 1592 respondents in Jakarta were analyzed through a cluster analysis using the statistical package for social sciences software. The hedonic price model with ordinary least squares regression was adopted to create a valuation model for the green spaces in 42 districts and 239 sub-districts across the five administrative cities.
FINDINGS: This study empirically shows that parks and urban forests increase land prices by 9.2, 17.1, and 19.2 percent, while cemeteries decrease them by 15 to 37.6 percent. Unlike most hedonic price model studies on the global north countries, which can be found in the literature, this work does not establish statistically significant relationships among urban forests, parks, cemeteries within a 0–500 meter radius, and land prices in Jakarta, but examines the economic value of green spaces, including their impact on land values and tax revenues. The land value increase is caused by the implementation of a beneficiary zoning levy within a designated impact zone of 0.5–2 kilometers. This study suggests policy implications, including the exploration of alternative financing mechanisms and the consideration of public preferences in urban development and financing policies.
CONCLUSION: The applicability of the hedonic price model in Jakarta's mature and privatized land market is confirmed in this work, proving the importance of considering environmental factors and green spaces in land transactions and conversion, property development, conservation, and urban green space design. The results provide valuable information to policymakers, property developers, and land use planners, thereby preventing the undervaluation of green spaces and facilitating informed decisions on planning and public investment. Urban and built environmental management can significantly benefit from these findings, particularly when considering the aspects of green space size, social functions, and ecosystem services to enhance Jakarta's planning and management practices.

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82	5	5

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INTRODUCTION

Urban green infrastructure (GI), specifically green open spaces (GOS), is significant in rapidly urbanizing areas. Green spaces play a crucial role in providing environmental, social, and economic benefits to urban ecosystems and positively contribute to the health and well-being of communities, particularly in low- and middle-income countries facing rapid urbanization (Shuvo *et al.*, 2020). The rapid urbanization of cities presents opportunities and challenges, striving to balance growth with sustainability, equity, and quality of life for all residents. Cities are experiencing rapid growth due to the expansion of urban areas, which alters the landscape characteristics and structure. The incorporation of GOS planning and policy-making serves as a strategic imperative in achieving a more nuanced comprehension of sustainable development (Setiowati *et al.*, 2022[b]). Urban GI and ecosystem services are important in making cities more resilient to climate change and natural disasters (Van Oijstaeijen *et al.*, 2020). The issue of greenhouse gas emissions originating from industrial activities carries profound implications not only solely on a global scale in relation to climate change, but also on the sustainability of urban environments (Hashim *et al.*, 2015). Urban areas often house industrial zones, and mitigating emissions is crucial for urban sustainability. GOS have become a valuable component that offers a complementary approach to emission reduction. Through strategic planning, GOS can contribute to emission mitigation and enhanced environmental quality and promote sustainable practices within an urban setting. The green information technology (IT) holds a significant potential for enhancing urban sustainability (Asadi *et al.*, 2021). Its adoption encompasses eco-friendly practices and technologies across various sectors, which may be extended to the GOS development and management. The integration of Green IT and GOS aligns with the broader goals of urban sustainability, addressing factors like environmental quality, resource efficiency, and overall quality of life (Khoshnava *et al.*, 2019). Living inside or near nature in urban environments provides well-being benefits (Fruth *et al.*, 2019). The introduced GI and ecosystem services can enhance the resilience of cities to climate change and natural disasters (Van Oijstaeijen *et al*,. 2020). Meanwhile, GOS constitute an integral facet of GI, representing a crucial urban sustainability component. Their prominence has increased in significance because urban green areas yield a multitude of environmental and health benefits. This importance was underscored during the Coronavirus disease 2019 (COVID-19) pandemic, exacerbated by population expansion and urbanization that led to a diminishing availability of green spaces. Therefore, GOS planning excels as a strategy for realizing the overarching goal of sustainable urban development (Chiesura, 2004). Bertram and Rehdanz (2015) stated that the GOS concept provides ecosystem and cultural services and microclimate stabilization through air filtration or cooling to reduce the heat island effect (Bowler *et al.*, 2010). The presence of GOS can also enhance carbon storage (Strohbach and Haase, 2012) and provide social, environmental, economic (Boone *et al.*, 2009; Wendel *et al.*, 2011), and psychological benefits for escaping the pressures and demands of urban life (Maller *et al.*, 2006). The social benefits include improved mental and physical health, stress reduction, and relaxation (Konijnendijk *et al.*, 2013; Setiowati *et al.*, 2022[a]). Urban GOS enhance the quality of life directly through recreational activities, sports, and social interaction (Kabisch and Haase, 2014; Setiowati *et al*,. 2022a). Furthermore, GOS assume a beneficial role in promoting public health (Shuvo *et al.*, 2020). The abovementioned findings show that GOS development can address various issues, including environmental justice, public health, and aesthetic and land value enhancement. The GOS concept enhances climate resilience by providing habitats for biodiversity and creating important externalities in policy design to ensure their sufficient presence in urban environments. GOS planning plays a key role in achieving sustainable urban development (Choumert and Salanié, 2008). Berlin and Leipzig in Germany target 6 meter square (m^2) and 10 m^2 of GOS per capita (Kabisch and Haase, 2014), while the United Kingdom has access to at least 2 hectares (ha) of green space within a 300 meter (m) distance from residential areas (Handley *et al.*, 2003). English Nature recommendations suggest that residents should live no more than 300 m from the nearest green space (Barbosa *et al.*, 2007). Access among different social groups varies, with poorer and older individuals being the highest social groups to enjoy public GOS (Barbosa *et al.*, 2007). The presence of GOS also offers diverse ecosystem services.

Accordingly, public preferences vary based on socio-demographic factors carrying different policy implications. According to the European Environment Agency, the recommended access is within a 15 min walk. Even though GOS have a significant economic value, the concept behind them is not considered in the urban planning decision-making process. Non-market goods or services play a fundamental role in economic valuation by encapsulating values beyond traditional market transactions (Abdullah *et al*., 2011). An economic valuation must be conducted to provide decision-makers with a clear understanding of these values. In addition, the assessment of the economic value of GOS yields an overview of the ecosystem benefits generated by urban GI and serves as a basis for sustainable urban planning. Local governments require the economic value in the urban planning decision-making process. Indonesia has its Minister of Environment and Forestry Regulation No. 15 of 2012 on the Economic Valuation Guidelines for Forest Ecosystems (MEFR, 2012). Based on the MAASPNLAR (2022) on the GOS provision, one of the functions of GOS is to provide a land enhancement guarantee. The GI can be economically viable. As a commitment to the development, local governments conduct economic valuation (Van Oijstaeijen *et al*., 2020). Furthermore, GOS provide ecosystem services that address disease, quality of life, and health (Wolch *et al*., 2014). Physical activity and social interaction are the most important benefits provided by parks in relation to the quality of life (Artmann *et al*,. 2017). The GOS concept offers economic benefits through property values (Trojanek *et al.*, 2018; Zhang *et al.*, 2013). A monetary valuation is used to assess GOS through ecosystem services to meet environmental, social, and economic goals (Bockarjova *et al*., 2020). Green space services tend to be less available when policy interventions are excluded (Smith *et al*., 2002); hence, greening efforts in communities enhance environmental attractiveness without land acquisition (Franco and Macdonald, 2018). GOS include city parks, forests, golf courses, sports fields, and undeveloped land on the outskirts of cities (Brander and Koetse, 2011). Green landscapes are in high demand within most developed countries, and urban management is expected to prevent sprawling in centers and their adjacent regions (Cavailhès *et al*., 2009). However, assessing the GOS value is challenging due to their abstract nature. The benefits of green space conservation policies are difficult to understand without economic value information. In the context of urban policy planning, economic valuation creates awareness of the importance of the economic value generated by urban GI. In Indonesia, studies on the concept remain limited, and the valuation approaches used are expected to increase. In terms of assessment, monetary valuation methods are being used to describe green space characteristics by capturing individual preferences (Tagliafierro *et al*., 2013). Bateman *et al.* (2002) explained that various valuation techniques can be used to measure the total economic value of environmental services, including stated preference (SP) and revealed preference (RP). The SP method estimates the value placed on non-market facilities by individuals to obtain economic value estimates (Choumert and Salanié, 2008), while the RP method uses the actual market behavior as a basis for estimating implicit values and involves direct observation or substitute markets (Hanley *et al*,. 2016). The most commonly used RP methods are the travel cost method, the hedonic pricing method or hedonic price model (HPM), and averting behavior. The hedonic theory states that property price differences are based on variations in the property characteristics introduced by Rosen (1974) and Freeman (1979). The property plays an important role in the context of sustainable development, requiring measurement and equal growth distribution (Aziz *et al*., 2021). It has economic significance for trade-off calculations, including untraded goods in the market (Freeman, 1979). Rosen (1974) also reported that a good can be broken down into the implicit marginal prices of each separate characteristic. The property value reflects an individual's willingness to pay for a better environmental quality (Tyrvainen, 1997). The assessment of green spaces through hedonic pricing is the most widely used approach (Czembrowski *et al*., 2019; Daams *et al*., 2019). In the context of this study, the HPM approach is selected as the most suitable valuation method for estimating public preference for urban GOS. However, note that other relevant approaches can also provide different insights into the GOS value and public preferences. The HPM technique uses econometric models to show preferences through the property market, particularly land prices, at a regional scale (Waltert and Schläpfer, 2010). The GOS value is calculated by analyzing market prices, such as transportation and housing. In the HPM, the property value and the presence of GOS are linked to several variables, including distance, scenery, and accessibility (Choumert and Salanié, 2008). The method is widely used to calculate the value of green spaces by incorporating individual preferences in the property market context. Even though extensive studies have been previously conducted in Global North countries, limited analysis has been performed in developing countries under the Global South, including Indonesia. The Global North and South concepts are used to describe the social, economic, and political differences between countries in the northern and southern parts of the world. In China, Qu *et al.* (2020) found that the development of environmental facilities, such as parks, in less developed areas is associated with improved transportation quality and commercial services. Therefore, green spaces significantly affect the regional development. However, limited analyses have been conducted on the HPM application for valuation. Only two instances of usage were identified in Indonesia. One is by Yusuf and Resosudarmo (2009) for assessing the air quality in Jakarta, and the other is by Suparman *et al.* (2016) for evaluating piped clean water in both urban and rural areas. The present study develops a preference model for GOS in Jakarta, focusing on the park, urban forest, and cemetery categories. A valuation model is established herein using the HPM preference approach, adopting the property market as a proxy for estimating implicit values. A valuation model for GOS is investigated through the HPM preference approach that uses the property market as a proxy to estimate the implicit values in developing countries. This study seeks to uncover GOS preferences by examining the relationships among green space attributes, environmental amenities, residential structures, and land prices. The HPM technique enables the identification of public preferences based on the property prices at the regional level. This work specifically aims to investigate the relationships among green space attributes, environmental amenities, residential structures, and land prices using the HPM approach, estimate the effects of GOS on land values, and analyze the policy implications of urban GOS valuation. This study hypothesizes that proximity to various GOS attributes increases the land prices, and that these attributes have different economic values. This work was conducted in Jakarta, Indonesia in 2023.

MATERIALS AND METHODS

Study area

The study was performed in Jakarta, which is the capital city of Indonesia (Fig. 1). Jakarta is a densely populated urban area that faces significant challenges in terms of environmental sustainability and quality of life. It is renowned for its rapid urbanization, elevated air pollution levels, and limited availability of green spaces. Understanding the dynamics of and perceptions on green spaces is crucial for developing effective urban planning strategies and enhacing the well-being of residents. As one of the world's megacities, Jakarta covers land and sea areas of 662.33 and 6977.5 kilometer square (km^2), respectively. It has the highest density (20,618 people/km^2) and total population (10,679,951 poeple) in Indonesia (Central Bureau of Statistics, 2023). The northern boundary is a 32 kilometer (km) coastline that serves as the estuary for 13 rivers, two canals, and two floodways. The majority of Jakarta Province's features lie below sea level during high tide, making certain areas susceptible to flooding caused by high rainfall and tidal waves. As depicted in Fig. 1, the western boundary of the study area is Banten Province, while its southern and eastern boundaries border West Java Province.

Data collection

Data were collected by distributing a questionnaire created through Google Forms. This questionnaire was distributed online in 2021 using various social media platforms. It comprised components related to residency, socioeconomic characteristics, and structural housing variables. This study targeted respondents from five administrative cities, namely South, North, East, West, and Central Jakarta, and included 239 out of the 261 neighborhoods. However, 22 neighborhoods did not have any respondents. These were six neighborhoods each in South, East, and West Jakarta and four in Central Jakarta. The final sample consisted of 1660 respondents representing the community in Jakarta Province. Fig. 2 presents the spatial data managed by the Jakarta Capital City Government (JCCG) through the "Jakarta Satu," which included parks, city parks, cemeteries, and urban forests.

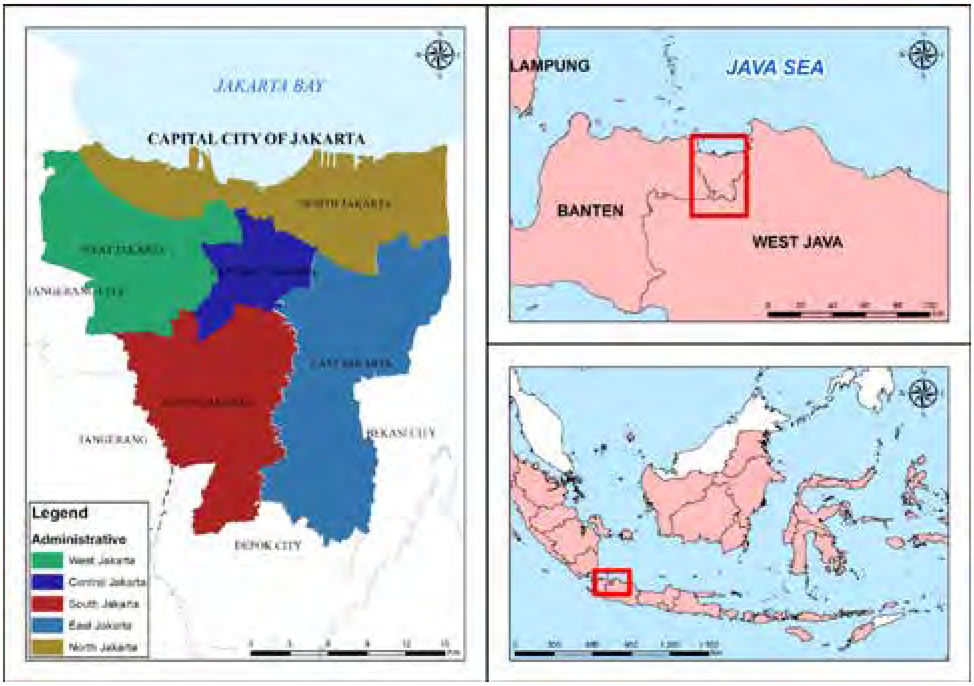

Fig. 1: Geographic location of the study area in Jakarta Capital City, Indonesia

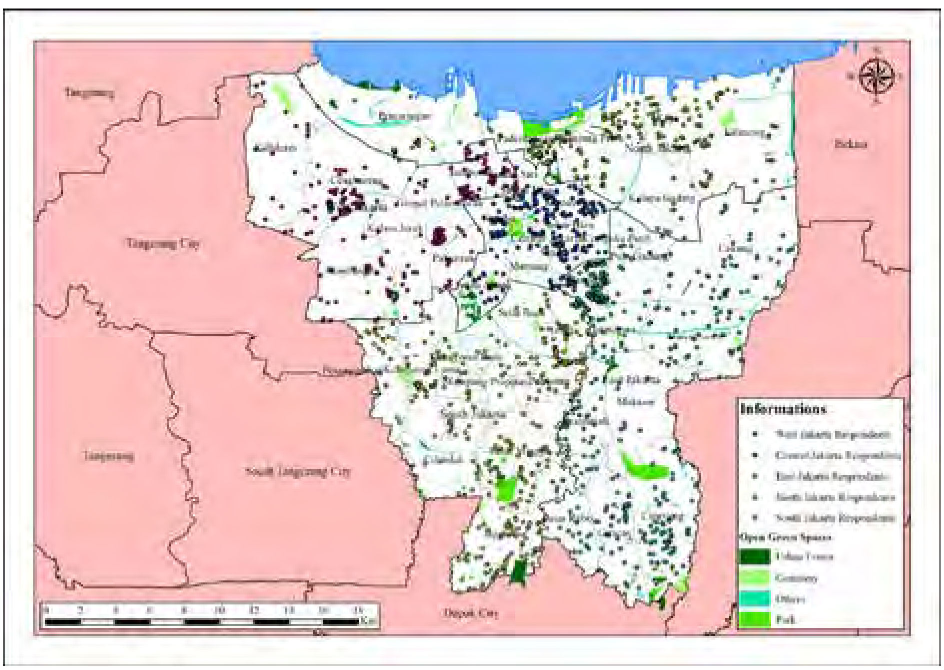

Fig. 2: Distribution of respondents and public GOS in Jakarta

Data analysis

After the data collection from 1660 respondents, a cluster analysis was performed using the Statistical Package for Social Sciences (SPSS) software to group respondents based on preference and reduce the data complexity. The dendrogram cluster analysis method, which is also known as hierarchical clustering, was used considering the socioeconomic characteristics of age, education level, occupation, and income. The dendrogram cluster analysis results using SPSS software showed the formation of two major clusters. Clusters 1 and comprised 1592 and 68 respondents, respectively. Cluster 1 with 1592 respondents was employed to create the GOS valuation model using the HPM preference approach with ordinary least squares (OLS) regression. The "distances from residential dwellings to environmental facilities" attribute, including proximity to GOS, was measured using the geographic information systems (GIS) software considering the questionnaire results. The "environmental facilities" variable included distances less than 1000 m to the highways, less than 200 m to rivers, less than 200 m to roads, less than 500 m to train stations, and less than 9000 m to central business districts (CBDs). The "distances of urban GOS" attribute from residential locations to public green spaces for models I and II was also computed using the GIS software. In Model I, the urban GOS attribute encompassed distances from the respondents' residential dwellings to parks, urban forests, and cemeteries, with a radius of less than 500 m. In Model II, the urban GOS were utilized as dummy variables for residential dwellings ranging from 0 to 2000 m, with subdivisions at 0–500, 500–1000, and 1000–2000 m for the park, urban forest, and cemetery catagories.

This study commenced with an initial phase involving a cluster analysis of the questionnaire responses using the SPSS software. Moreover, the variables were used to construct the HPM with the independent variables of environmental facilities, house structural characteristics, and attributes associated with urban GOS. A spatial analysis through GIS software was performed to calculate the distances from each respondent's residence to the GOS attributes and various environmental facilities. As independent variables, the environmental facilities relied on secondary data sources, including the number of public high schools, shopping centers, and population density. The house structural attribute (clean water source) was derived from the questionnaire. In the next step, an OLS model statistical analysis was performed using SPSS for both models I and II. The final step involved a comprehensive descriptive analysis for assessing the estimated values associated with the GOS attributes based on the OLS coefficients and the average land prices. Fig. 3 ilustrates the study framework.

Following Dahal *et al.* (2019), the land value (Pi) was used as a dependent variable, while the housing structure (Sij), environmental facilities (Nik), and urban green spaces (Eil) were treated as independent variables. The logarithmic form of the hedonic price function is presented using Eq. 1 (Dahal *et al*., 2019):

$$\ln Pi = \beta + \beta j Sij + \beta k Nik + \beta l Eil + \varepsilon \qquad (1)$$

where, β represents the intercept term; βj, βk, and βl are the coefficients corresponding to the respective independent variables; and ε denotes the error term. The equation suggests that the land price logarithm is a function of the housing structure, environmental facilities, and urban green spaces, each with respective coefficients. The error term accounted for any unobserved factor or measurement error. A global model (OLS regression) was adopted herein using the land price market in Jakarta to estimate the implicit marginal prices of the housing structure attributes, environmental facilities, and urban green spaces. The implicit prices of each variable characterized the land price as an HPM function derivative. This refers to the land value representing the marginal prices of each variable. The environmental facility variables are not directly purchased and included in the land price, but the monetary value is shown through the prices paid by the buyers for the land. The equation for the implicit price function adopts this approach, where *Zi* is the land attributa vector, using Eq. 2 (Dahal *et al,*. 2019).

$$PZi(Zi, Zi-1) = \frac{\partial P(Z)}{\partial Zi} \qquad (2)$$

where, *PZi* denotes the implicit price of the land attribute *Zi*, and $\frac{\partial P(Z)}{\partial Zi}$ represents the partial derivative of the price *P* to the attribute *Zi*. This equation estimates the marginal implicit prices associated with each land attribute in the HPM context, namely models I and II at 640 and 1592 samples, respectively, with differences in the GOS criteria. Table 1 shows

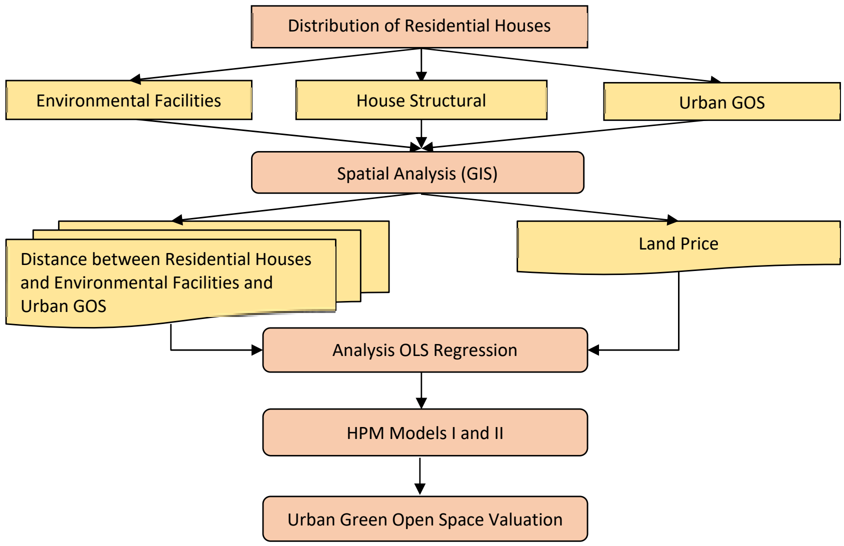

Fig. 3: Study framework

Table 1: Descriptive statistics

Variables	Model I		Model II	
	Mean	SD	Mean	SD
Intercept	15.6582	0.91708	15.7521	0.91550
Residential structure variable				
Clean water source as a dummy variable	0.4469	0.49756	0.4912	0.50008
Environmental/locational facility variable				
Number of public high schools	2.7922	1.67152	2.6376	1.65805
Number of the shopping center	17.0156	6.43152	16.7714	6.01814
Population density	23347.4891	16482.78474	25605.8304	18607.54882
Respondent's location	2.6063	1.36968	2.8536	1.40102
Distance to toll road (1000 m) as a dummy variable	0.4453	0.49739	0.4083	0.49167
Distance to the main road (200 m) as a dummy variable	0.1859	0.38936	0.1859	0.38917
Distance to train station (500 m) as a dummy variable	0.1000	0.30023	0.1043	0.30571
Distance to CBD (9000 m) as a dummy variable	0.5047	0.50037	0.5396	0.49859
Distance to the river (200 m) as a dummy variable	0.2875	0.45295	0.2808	0.44952
Urban GOS variable				
Urban forest				
Less than 500 m	78.4547	145.89117		
0–500 m as a dummy variable			0.1118	0.31523
500–1000 m as a dummy variable			0.1916	0.39367
1000–2000 m as a dummy variable			0.3386	0.47337
Park				
Less than 500 m	182.6344	177.34022		
0–500 m as a dummy variable			0.2494	0.43279
500–1000 m as a dummy variable			0.2739	0.44608
1000–2000 m as a dummy variable			0.3097	0.46250
Cemetery				
Less than 500 m	101.3172	159.79211		
0–500 m as a dummy variable			0.1420	0.34912
500–1000 m as a dummy variable			0.3656	0.48174
1000–2000 m as a dummy variable			0.3461	0.47588

a descriptive analysis of the mean and standard deviation (SD) using SPSS.

Waltert and Schläpfer (2010) underscored the propensity for regions endowed with comprehensive amenities to exhibit accelerated growth, suggesting the potential synergy between hedonic pricing studies and economic and regional migration models. This dynamic interplay, relationships among landscape amenities, developmental patterns, environmental policies, and property prices furnished a comprehension of landscape and economic governance. The escalating urban land and housing prices have assumed paramount significance, prompting policymakers to contemplate on regulatory interventions. These interventions entail the systematic multifarious determinants influencing the land and housing prices, which encompass the socioeconomic profile of the populace, proximity to urban cores and CBDs, accessibility to transportation networks, and proximity to urban facilities surrounding green spaces, parks, sports amenities, and healthcare centers (Mirkatouli *et al.,* 2018). Incorporating the role of both dependent and independent variables is important in augmenting the nation's economic value.

RESULTS AND DISCUSSION

Valuation of GOS using the hedonic price model

The variables in the valuation model analyzed using the HPM approach were the residential structure, environmental facilities, and urban GOS. The urban GOS valuation was formulated by following two steps with the OLS regression model implementation. The regression estimated the coefficient parameters of the independent variables to determine the positive or negative influence on the urban GOS valuation. The results analyzed the effect of the independent variables. The estimated coefficients indicated the positive or negative effect on the land prices. The OLS model adopted a semilog approach following the methodology used by Dahal *et al.* (2019). The data analysis using the SPSS yielded coefficient parameter estimates with varying degrees of influence. Not all independent variables produced statistically significant results. The estimation was obtained by multiplying the percentage with the average land price zoning. Classic assumption tests ensured that the data met the requirements. The normality test performed using a P-plot graph reported that the data followed a normal distribution. Table 2 shows the description and expected signs of variables in the hedonic price model.

Dependent variable: Land price

The HPM typically employs property prices as a dependent variable; however, due to the unavailability of property data in Indonesia, this study utilized land prices, depicting a consistent approach with the previous HPM studies (Gao and Asami, 2007; Mirkatouli *et al.,* 2018). Land prices constitute a primary determinant of housing costs (Shen and Karimi, 2017). Yu (2010) elucidated that land prices and income influence property prices. Abelson (1985) posited that land prices are expected to feature as a variable in housing prices and estimated to be five times the housing price. A critical issue in urban areas is land scarcity (Zhong *et al.,* 2016). The confluence of limited land supply, escalating demand, and rural-to-urban migration precipitated rapid land and housing price increases. Accompanied by their marginal effects, the compatibility of buildings with green environments significantly affects land prices (Gao and Asami, 2007). Land is a requisite resource of all economic activities (Nichols *et al.,* 2013), rendering it a fundamental component in urban development and expansion (Li *et al.,* 2016). The land price is a dependent variable based on the National Land Agency of Jakarta Province and distributed zoning (Fig. 4). In the first stage, the multiplication of coefficients with 100 percent (%) yielded the results. In the second stage, the percentage was multiplied by the average land price zoning for the 1592 respondents, which was Rp10,900,575. The GOS externalities in urban planning and development policies are difficult to assess. The government of Jakarta and the city's private developers have not objectively included the GOS attributes in land pricing and spatial planning policies. The HPM offers an appropriate approach of estimating the external benefits of the urban GOS, contributing to land prices. This study explored the major impact of environmental elements influencing the land prices in Jakarta, Indonesia. A semilog approach OLS model was used by transforming the dependent variable (i.e., land price) in line with the work of Dahal *et al.* (2019).

Table 2: Description and expected signs of the HPM variables

Variable	Description	Expected sign	
		Model I	Model II
Dependent variable			
Land price	Zoning price of residential land based on data from the National Land Agency of DKI Jakarta Province		
Independent variable			
Residential structure			
Clean water source	Dummy variable, s = 1 for clean water source from the pipeline, s = 0 for clean water source non-pipeline	+/−	+/−
Environmental/location facilities			
Public high schools	Number of public high schools at the sub-district level	+	+
Shopping center	Number of shopping centers at the administrative city level	+	+
Population density	Population density per village	−	−
Distance to toll road	Dummy variable, s = 1 for residential locations within 1000 m from the toll road, s = 0 for residential locations beyond 1000 m from the toll road	+/−	+/−
Distance to road	Dummy variable, s = 1 for residential locations within 200 m from the road, s = 0 for residential locations beyond 200 m from the road	+	+
Distance to train station	Dummy variable, s = 1 for residential locations within 500 m from the train station, s = 0 for residential locations beyond 500 m from the train station	+	+
Distance to CBD	Dummy variable, s = 1 for residential locations within 9000 m from the CBD, s = 0 for residential locations beyond 9000 m from the CBD	+	+
Distance to river	Dummy variable, s = 1 for residential locations within 200 m from the river, s = 0 for residential locations beyond 200 m from the river	+/−	+/−
Location	Location of respondent's residence per administrative city (1, 2, 3, 4, and 5 for South, East, North, West, and Central Jakarta, respectively)	+/−	+/−
Green open space			
Distance to urban forest	Residential location to the nearest park within 500 m	+	
0–500 m	Dummy, s = 1 for residential locations within a distance of 0–500 m from the park, s = 0 for residential locations not within a distance of 0–500 m from the park		+
500–1000 m	Dummy, s = 1 for residential locations within a distance of 500–1000 m from the park, s = 1 for residential locations not within a distance of 500–1000 m from the park		+
1000–2000 m	Dummy, s = 1 for residential locations within a distance of 1000–2000 m from the park, s = 0 for residential locations not within a distance of 1000–2000 m from the park		+
Distance to park	Residential location to the nearest park within 500 m	+	
0–500 m	Dummy, s = 1 for residential locations within a distance of 0–500 m from the park, s = 0 for residential locations not within a distance of 0–500 m from the park		+
500–1000 m	Dummy, s = 1 for residential locations within a distance of 500–1000 m from the park, s = 1 for residential locations not within a distance of 500–1000 m from the park		+
1000–2000 m	Dummy, s = 1 for residential locations within a distance of 1000–2000 m from the park, s = 0 for residential locations within a distance of 1000–2000 m from the park		+
Distance to cemetery	Residential location to the nearest cemetery within 500 m	−	
0–500 m	Dummy, s = 1 for residential locations within a distance of 0–500 m from the park, s = 1 for residential locations not within a distance of 0–500 m from the park		−
500–1000 m	Dummy, s = 1 for residential locations within a distance of 500 –1000 m from the cemetery, s = 1 for residential locations not within a distance of 500–1000 m from the cemetery		−
1000–2000 m	Dummy, s =1 for residential locations within a distance of 1000–2000 m from the cemetery, s = 0 for residential locations not within a distance of 1000–2000 m from the cemetery		−

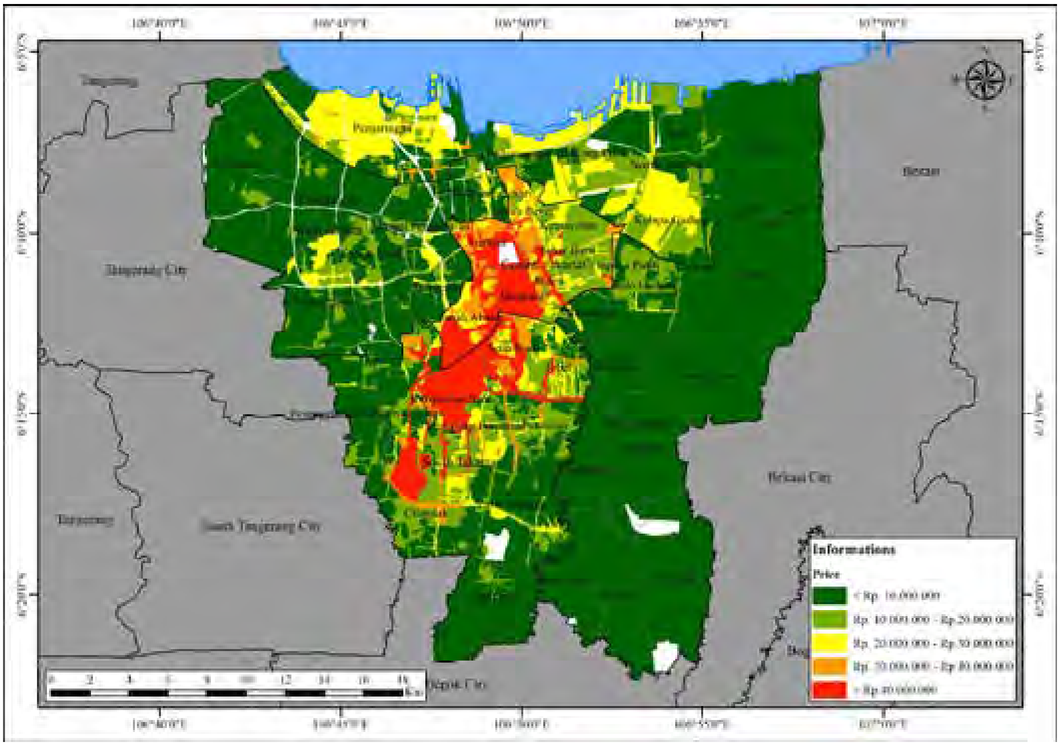

Fig. 4: Land price zoning in Jakarta

Independent variable

Urban GOS

Chiesura (2004) found a relationship between GOS and their ultimate contribution to an improved quality of life and the pursuit of sustainable urban development. Urban areas rich in greenery offer urban residents a serene and pleasant living environment (Sturm and Cohen, 2014). The GOS valuation model using the HPM estimated the community's preferences for urban GOS based on predetermined attributes. In this context, the valuation aimed to determine the economic value of urban GOS and the influencing factors. This model provides a community preference and assigns an economic value to these attributes in the urban GOS context. A better understanding of preferences provides a valuable guidance for policymakers in making decisions related to the development and management of urban GOS in Jakarta. In 2019, the JCCG input the spatial data of public GOS assets owned and managed by various departments into the Jakarta Satu website. The asset data showed that the total area of GOS was approximately 5.1% of the total land area. Jakarta has also implemented the Regional Regulation Number 1 of 2012 Concerning Spatial Planning 2030, with the ambitious objective of reaching a 30% GOS in accordance with the provisions set forth in Law No. 26 of the Republic of Indonesia (Law, 2007).

Environmental facilities

According to previous studies, the environmental facility variables in the HPM model included school quality, average income, hospitals, crime rates, and demographics. These variables were developed from the number of public high schools per sub-district, shopping center, population density per village, respondent location, and distances to toll and main roads, train stations, rivers, and CBDs. An important characteristic of the surrounding environment is network connectivity or accessibility measured by main and toll roads, public transportation, and distance to the city center or CBDs. Moreover, transportation infrastructure variables have positive and negative impacts (Czembrowski and Kronenberg,

Table 3: Model summary

Model	R	R^2	Adjusted R^2	SE of the estimate	Durbin–Watson table (DW)	Durbin–Watson (D)
II	0.765	0.585	0.580	0.59354	1.908	1.912

2016; Kong *et al*,. 2017). The data on the number of public schools were obtained from the JCCG website.

Housing structure

The structural house from the questionnaire comprised the number of rooms, bathroom location, clean water source, and building size. Only the clean water source variable was input into the model during the valuation process. Respondents with non-pipeline and pipeline clean water sources accounted for 50.78 (843) and 49.25% (817), respectively. South and North Jakarta showed the lowest and highest portions of respondents with pipeline water sources, depicting values of 13.24 and 85.00%, respectively. The pipelines in South Jakarta are not distributed; hence, residents rely on groundwater as clean water. This limited availability in North Jakarta has led the majority of its population to prefer pipelines as a clean water source.

Hedonic price model OLS regression

The model was validated based on the classical assumptions encompassing tests for normality, multicollinearity, heteroskedasticity, and autocorrelation. Normality testing involves the use of a visual P-plot, indicating that the data distribution closely adhered to the diagonal axis signifying a normal distribution. In this study, the Durbin–Watson table (DW) for autocorrelation testing and the SPSS output yielded a D value of 1.912. Referring to the DW table at a 0.05 significance level, the DW value was 1.908. No autocorrelation was found within the testing range of 1.908 < 1.912 < 2.14 (Table 3).

The test for multicollinearity was determined by the tolerance values and the variance inflation factor (VIF). The tolerance value measures the variability of the independent variable that cannot be explained by other independent variables. Accordingly, a low value corresponds to a high VIF value because VIF = 1/tolerance, indicating a high collinearity. The cut-off used is a tolerance value above 0.10 or a VIF below 10. Model II of the HPM approach showed a value above 0.10 and a VIF below 10, showing the absence of multicollinearity. The heteroscedasticity test using a scatterplot graph revealed that the data points followed a diagonal axis, confirming a normal distribution. This model satisfied the classical assumptions and can be used to analyze the relationship between independent and dependent variables. The statistical analysis results also showed the relationship between urban green space variables and land prices in a specific context. The analyzed GOS variables and distance radius can have different effects on land prices. These observed effects vary depending on the complexity of other factors influencing the land prices and the specific urban environment characteristics. The variable insignificance may be influenced by unexamined factors or the utilized sample size. Therefore, further exploration and additional studies are important for understanding the relationship between urban GOS variables and land prices. Table 4 shows the estimates from the HPM models used to analyze the GOS monetary value.

Model I of the OLS approach using the HPM showed an R-squared (R^2) value of 0.561 or 56.1%, depicting a moderately strong relationship using Eq. 3 (Dahal *et al.,* 2019). The independent variables collectively accounted for 56.1% of the land price variation. Model II yielded a higher R^2 value amounting to 0.585 or 58.5%. The independent variables were 58.5% of the land price variation, as obtained using Eq. 4 (Dahal *et al.,* 2019). Model I analyzed three GOS variables, namely urban forests, parks, and cemeteries, within a radius fewer than 500 m. Model II examined nine GOS variables, namely urban forests, parks, and cemeteries within the three distance ranges of 0–500 m, 500–1000 m, and 1000–2000 m represented as dummy variables.

LnLand price = 13,505 + 0.243 (clean water source) + 0.016 (public high school) + 0.060 (shopping center) − 4.640E−06 (population density) + 0.284 (respondent's location) − 0.091 (toll road) + 0.253 (road) + 0.048 (train station) + 0.639 (CBD) − 0.064 (river) + 5.444E−05 (distance to urban forest less than

500 m) + 0.000 (distance to park less than 500 m) − 3.378E−05 (distance to cemetery less than 500 m) + e (3)

Lnlandprice = 13.636 + 0.096 (clean water source) + 0.032 (public high school) + 0.065 (shopping center) − 4.711E−06 (population density) + 0.262 (respondent's location) − 0.049 (toll road) + 0.206 (road) + 0.000 (train station) + 0.593 (CBD) − 0.026 (river) − 0.044 (distance to urban forest less than 500 m) + 0.171 (distance to urban forest 500 m–1000 m) + 0.192 (distance to urban forest 1000 m–2000 m) + 0.029 (distance to park less than 500 m) + 0.092 (distance to park 500 m–1000 m) − 0.020 (distance to park 1000 m–2000 m) + 0.032 (distance to cemetery less than 500 m) − 0.376 (distance to cemetery 500 m–1000 m) − 0.150 (distance to cemetery 1000 m–2000 m) + e (4)

The results indicated that only five variables in Model II had a significant relationship and provided negative and positive influences on the land prices. In Model I, the coefficient values for

Table 4: Estimates from the HPM models used to estimate the GOS monetary value

Variables	Coefficient		Coefficient	
	Model I	Model II	Tolerance value	VIF
Intercept	13.505	13.636		
Residential structure variable				
Clean water source as a dummy variable	0.243***	0.096***	0.796	1.256
Environmental/locational facility variable				
Number of public high schools	0.016	0.032***	0.672	1.489
Number of the shopping center	0.060***	0.,065***	0.584	1.711
Population density	−4.640E−06**	−4.711E−06***	0,643	1.554
Respondent's location	0.284***	0.262***	0.550	1.819
Distance to toll road (1000 m) as a dummy variable	−0.091*	−0.049	0.820	1.219
Distance to the main road (200 m) as a dummy variable	0.253***	0.206***	0.922	1.085
Distance to train station (500 m) as a dummy variable	0.048	0.000	0.823	1.215
Distance to CBDs (9000 m) as a dummy variable	0.639***	0.593***	0.565	1.769
Distance to the river (200 m) as a dummy variable	−0.064	−0.026	0.890	1.123
Urban GOS variable				
Urban forest				
Less than 500 m	5.444E−05			
0–500 m as a dummy variable		−0.044	0.855	1.169
500–1000 m as a dummy variable		0.171***	0.693	1.443
1000–2000 m as a dummy variable		0.192***	0.723	1.384
Park				
Less than 500 m	0.000			
0–500 m as a dummy variable		0.029	0.735	1.361
500–1000 m as a dummy variable		0.092**	0.611	1.637
1000–2000 m as a dummy variable		−0.020	0.661	1.512
Cemetery				
Less than 500 m	−3.378E−05			
0–500 m as a dummy variable		0.032	0.910	1.099
500–1000 m as a dummy variable		−0.376***	0.510	1.961
1000–2000 m as a dummy variable		−0.150***	0.556	1.797
Model summary				
R-squared	0.561	0.585		
Adjusted R-squared	0.552	0.580		
N	640	1592		
Significance levels: ***0.01, **0.05, and *0.1				

Table 5: Estimation of the effects of GOS on the land price in Model II

Variable urban GOS	Effects on land prices (%)
Distance to an urban forest 500–1000 m	17.1***
Distance to an urban forest 1000–2000 m	19.2***
Distance to park 500–1000 m	9.2**
Distance to cemetery 500–1000 m	−37.6***
Distance to cemetery 1000–2000 m	−15***

Significance levels: ***0.01 and **0.05

the GOS variables were not statistically significant and lacked a significant impact on the land prices. Dummy variables were used in Model II to analyze the spatial location of properties. The urban forest variable located between 500 and 1000 m from the residential area showed a 17.1% increase in the land prices. The highest influence was found in the urban forest with the 1000–2000 m distance, illustrating a 19.2% land price increase. For the parks, a significant influence in the 500–1000 m distance was observed with an average 9.2% land price increase. However, in other distances, the park category did not share any significant impact on the land prices. The cemetery variable decreased the land prices within the distance ranges of 500–1000 m and 1000–2000 m, depicting 37.6 and 15% of land price decreases, respectively. Model II represented residential locations within 0–500 m from the urban forest, showing a 0.044 coefficient, which negatively affected the land price. The parks did not have a significant influence within the two distance categories of 0–500 m and 1000–2000 m with coefficients of 0.029 and 0.020, respectively, thereby showing decreasing land prices. The cemetery variable yielded a positive coefficient, but was not significant in the 0–500 m distance with a 0.032 coefficient. The study did not confirm that all GOS aspects were equally desired by the land buyers in Jakarta. However, the impact of different GOS categories varied, aligning with the hypothesis. The HPM approach had limitations, including the possibility that not all independent variables have a linear relationship due to heterogeneity effects (Ligus and Peternek, 2016). Table 5 presents an estimation of the effects of GOS on the land price in Model II.

Other factors influencing the relationship between independent variables and land prices must be considered. The analysis of the housing structure variables showed that the “clean water source” with a positive coefficient of 0.096 was significant at the 99% level. Therefore, having access to clean water from a public utility has a positive influence on land prices. Not all environmental facility variables had a significant positive impact. Shopping centers, locations of the respondents’ residences, public high schools, roads within a distance fewer than 200 m, and CBDs demonstrated significant positive coefficients on land prices, while population density showed a significant negative effect. The coefficients for the variables of shopping center, location, public high schools, roads within a distance less than 200 m, and CBDs with a 9000 m radius were 0.065, 0.0262, 0.032, 0.206, and 0.593, respectively, indicating positive influences on land prices. The population density variable yielded a negative and significant coefficient of 0.00000471, showing that a population density increase was associated with a land price decrease. The physical development pattern of Jakarta is initially directed within a 15 km radius of the National Monument (Jakarta Master Plan 1965–1985). Therefore, the highest land prices in Jakarta are concentrated in Central Jakarta following the land-use development pattern for commercial and office purposes. The highest coefficient influencing 59.3% of land prices was the distance to the CBD, which was consistent with the results obtained by Lewis (2007), showing that the increase in land prices per 1 km of distance to the CBD was 5.4%. This finding was also supported by Lewis (2007) and Mirkatouli *et al.* (2018), who suggested that proximity to the city center is a preference in selecting a place of residence. The analysis of environmental facilities confirmed that several variables do not have a significant relationship with land prices. The distance to the toll road less than 1000 m had a 0.049 coefficient with negative and insignificant effects. The distance to the train station less than 500 m showed a 0.0002 coefficient with positive and insignificant effects. The distance to the river within less than 200 m yielded a 0.026 coefficient with negative and insignificant effects on land prices. The key variables in constructing the OLS valuation model for urban green spaces with a significant relationship with land prices were found to be clean water sources, location of the respondents' residence at the city level, roads, and presence of CBDs. Therefore, these variables significantly influenced the land prices in Jakarta. The subsequent step here was to estimate the value of urban green spaces based on the percentage effects derived from the OLS coefficients multiplied by the average zona land price. The highest increase in land prices was found in locations with a 1000 to 2000 m a distance range from the urban forest, depicting an increase of Rp2,092,910. The second-highest and highest increments were observed in the 500 to 1000 m range, with increases of Rp1,863,998 and Rp1,002,853, respectively. Conversely, the highest decrement occurred in residential areas with 500 to 1000 m and 1000 to 2000 m distance ranges from the cemetery at Rp4,098,616 and Rp1,635,086, respectively. These findings were consistent with those of Kong *et al.* (2007), Tyrväinen and Miettinen (2000), and Samad *et al.* (2020). According to Morancho (2003), Larson and Perrings (2013), Anderson and West (2006), and Lutzenhiser and Netusil (2001), the land value increase in the presence of urban forests indicates that larger green spaces have a positive relationship. This finding was consistent with that obtained by Czembrowski and Kronenberg (2016), who stated that different types of green spaces have different impacts, and the strongest effect occurs in residential areas near the unique and popular Lagiewniki Forest. This finding was also in line with those of Czembrowski and Kronenberg (2016), whose results showed that parks and urban forests have a significant positive impact on property prices, while cemeteries decrease the variable. These results were consistent with those found by Tyrväinen and Miettinen (2000) and Larson and Perrings (2013), who found positive impacts on extensive forests and large parks. The negative impact of cemeteries on property prices was also found in the studies of Andersson *et al.* (2007), Raymond and Love (2000), and Anderson and West (2006). However, these findings were inconsistent with the results of Lutzenhiser and Netusil (2001) on their study area of Oregon, United States. They found that proximity to cemeteries does not have a significant relationship with the property prices. The current study provides evidence supporting the idea that the residential land value can be influenced by environmental factors, such as GOS. The effects of specific GOS types can vary, and specific contexts must be considered in land value assessments. The land market in Jakarta is mature and capable of showing significant relationships between prices and structural, environmental/location, and GOS attributes. Differences also exist in the impact of proximity to certain GOS types. These include urban forests, parks, and cemeteries. The presence of cemeteries is an undesirable facility for land buyers in Jakarta. In models I and II using the HPM, no significant relationships were found among parks, urban forests, cemeteries, and land prices within a 500 m radius. Even though GOS have direct access to the community, pragmatic thinking in a hedonic behavior may be a factor influencing the result. The usage of a 500 m radius as a buffer takes reference from previous studies (Czembrowski and Kronenberg, 2016; Czembrowski *et al*., 2019; Daams *et al*., 2019) in Western countries. For example, the findings of Czembrowski and Kronenberg (2016), Melichar and Kaprová (2013), and Daams *et al.* (2019) showed a significant positive relationship between the percentage of greenery within a 500 m radius and the property prices in Finland, Prague, and Amsterdam, respectively. These findings were inconsistent with the results obtained by Tyrvainen (1997), who found a negative impact of living close to urban forests due to vegetation density. According to Kong *et al.* (2007), in Jinan (China), green spaces within a 300 m radius can increase property prices by approximately 2.1%. In conclusion, Western theories cannot always be directly applied to public spaces. Therefore, environmental factors and GOS can have complex and varied impacts on land prices. The social, cultural, and local policy contexts must be considered when trying to understand the relationship between GOS and land values in Indonesia. The greatest positive impact of the presence of urban forests and parks was in line with the results of several previous studies. The residents of Jakarta highly value direct access to urban forests and parks. The monetary valuation of GOS has become important in high-density residential environments in Jakarta, as found by Daams *et al.* (2019) who studied the metropolitan city of Amsterdam. Daams *et al.* (2019) investigated the distance from homes, finding that the estimate does not affect GOS beyond 1 km. The varying radius division results were consistent with the findings of the estimated effects of GOS ranging from 7.1 to 9.3% within 0.25 km from the nearest green space from 1.7 to 2.3% within a distance of 0.75 to 1.0 km. With China as their study area, Qu *et al.* (2020) found a significant positive relationship between land prices and parks within the distance of up to 1600 m, but did not explain the relationship within the radius less than 500 m. The results were consistent with those of studies conducted in other developing countries. For example, Biao *et al.* (2012) stated that in Beijing (China), the value of properties lies within a distance of 850–1604 m from parks, with property prices increasing between 0.5 and 14.1%. Islam *et al.* (2020) found that, in Bangladesh, open spaces within 0–1000 m had a negative and insignificant relationship with house rental prices. Sharma and Newman (2018) reported in Bangalore (India), a negative relationship exists between the presence of parks and property prices. Li *et al.* (2021) found that, in Shenzhen (China), a negative relationship can be found between the presence of community parks within a 0–1000 m radius of residences. These findings complemented the limited literature on urban green space valuation in developing countries (e.g., Aziz *et al.* (2021)). Therefore, the HPM can be applied in the context of Jakarta, which has a growing and privatized land market. The results can provide policymakers and property developers with information on land transactions and conversion, property development, conservation, and ecologically sound urban green space designs. This study has implications for land use planning and public investment in densely populated areas like Jakarta. Green spaces often compete with other land uses and are undervalued by the public and their policymakers. These findings can prevent the undervaluation of green spaces and provide additional policymakers with information on the implicit value of green spaces, consequently enhancing the value of these areas. The development of Jakarta often overlooks the presence of green spaces, even though Engström and Gren (2017) showed a relationship between green spaces and health. Valuing green spaces can enhance our understanding of their benefits and provide support to city planners. This study is an important step in creating policy implications related to the monetary valuation of GOS for local governments. Local governments may increase their tax revenues by developing, expanding, and maintaining GOS. This study makes a significant contribution to understanding the role of urban forests and parks in the context of Jakarta, showing their significant impact on land prices. However, further studies can be performed to deepen our understanding of GOS. Future studies can expand the GOS valuation by considering various aspects, such as the size of green spaces, related social functions, and ecosystem services, using comprehensive models with more variables. This will enrich one's understanding of the relationship between GOS and land value and provide a more comprehensive perspective on green space planning and management. For the valuation model development using the HPM approach, a large sample size is required at the regional scale to obtain significant relationships. The findings obtained here were in line with those of Waltert and Schläpfer (2010), who found more significant relationships in urban areas compared to rural or remote areas. At the provincial level, 12 significant independent variables were determined out of 19 used ones concerning land prices. The key variable in the OLS model was found to be the availability of clean water sources in residential areas, which has a significant positive influence on land prices. The presence of toll roads did not have a significant relationship at the provincial level; however, in Central Jakarta, this variable depicted a significant negative relationship with land prices, yielding a 37.4% coefficient. Empirical evidence showed that toll roads in Jakarta are located in border areas with other administrative cities, and that these areas tend to be dense and irregular. The presence of dense and irregular settlements affects the land price decrease. The population density variable statistically had a significant negative relationship with the land prices in the five administrative cities, even though the influence was relatively small. The presence of public high schools also had a significant relationship and a positive association with average land prices. The proximity to roads variable showed a positive and significant relationship at the provincial level. However, the variable with the highest influence was the distance from the residential areas to the CBDs, which exhibited a positive and significant relationship with land prices. The valuation of green spaces can be conducted through the HPM approach, which provides a better understanding of the economic value of these spaces in enhancing the value of an area. Green spaces are not only seen as zoning areas or urban spatial patterns, but also as public investments with an economic value. Green spaces must be protected and developed in urban areas considering their environmental, economic, and social benefits. This study demonstrated that the presence of parks and urban forests can increase the land prices in Jakarta, which was consistent with the hedonic valuation literature showing the important role of green spaces as property price determinants (Daams *et al*,. 2019). The HPM study provided an understanding of the dynamic interaction existing among the land prices, environmental amenities, housing structure, and GOS. The valuation model did not have a higher R^2 value compared to the provincial level, affirming that the HPM model can be applied at the regional scale, as stated by Waltert and Schläpfer (2010) and Palmquist (2005). The paradigm on GOS also shifted as part of the GI concept with an economic value in enhancing the value of an area. However, the existence of green spaces is increasingly being threatened, with the high land prices posing a challenge in financing sustainable green space development. In developing GOS, creative thinking is needed to ensure the greening of public spaces to meet the needs of areas with a limited land availability. The GOS development is limited to the existing environmental quality, thereby requiring an understanding of how the distribution and functions provide the spaces' economic value. Cultural ecosystem services are becoming increasingly important with the population growth and the challenges of urban life.

Policy implications of the urban GOS valuation

As substantiated by the empirical investigations conducted by Setiowati *et al.* (2019) and Budiman *et al.* (2014), the annual decrement in the presence of GOS in Jakarta signifies a diminishing emphasis on GOS within the broader Jakarta metropolitan region. This discernment implied that the significance and the intrinsic value of GOS in the urban fabric may not have been afforded the requisite attention and appreciation. The stewardship of the GOS development in Jakarta transcends the realm of the local governmental authority and necessitates the active participation of a diverse array of stakeholders from the private sector. The target for private GOS in Indonesia, which has been mandated to be provided by both the community and the private sector, is set at 10% in accordance with Law 26 of 2007 (Law, 2017). As suggested by Alterman (2012), the economic value of green spaces indicates the need for continued policies in valuing the green spaces integrated with the Land Value Captured (LVC) concept through land price increases and as alternative funding sources for public investments. The green spaces in Indonesia must be seen as infrastructure and public investments that generate an economic value in urban area enhancement. Therefore, the LVC concept has a potential and needs further development with the use of more parameters to explore the impact of urban green space accessibility on the area value enhancement. The study suggests the need for developing more urban forests, parks, and cemeteries in Jakarta with good landscape architecture and aesthetics. The existence of cemeteries in Jakarta is primarily marked by an unsettling and disorganized atmosphere, which is inadequately addressed by the JCCG. Mitigating the negative impact of cemeteries on land values requires the JCCG to improve the quality and management of cemeteries scattered throughout Jakarta to make them less ominous and more suitable for recreational activities. The increased willingness to pay drives policy changes and density zoning that benefit the land market by promoting optimal value and use. The results can benefit policymakers when building green space infrastructures, such as parks and urban forests, as maximum efforts in urban economic development. The results of this work can also be used as input in drafting the Presidential Regulation on Area Value Improvement Management in collaboration with the Coordinating Ministry for Economic Affairs and the Asian Development Bank. The sustainable development in developing countries requires a study that addresses strategic issues like green spaces. Environmental amenities are regarded as social infrastructure in developing countries. This study provides strong evidence that parks and urban forests have statistically significant positive effects on land price vicinity. The findings obtained are largely consistent with those of previous HPM studies in the Global North countries despite the differences in the captured effects within the 0–500 m radius. This study found no significant relationship between the presence of GOS within the 0–500 m radius and the land prices in Jakarta, differing from most of the HPM studies found in the literature that utilized Global North countries as their study areas and showing a significant relationship within a 500 m radius similar to Daams *et al.* (2019) and Czembrowski and Kronenberg (2016) in line with the World Health Organization's standard of GOS presence from residential areas at 300 m. The results acquired in this work align with the findings of studies conducted in the Global South countries, which did not establish a significant connection to the land value within a 500 m radius of green spaces. This consistency was in line with the studies of Biao *et al.* (2012) for Beijing (China), Islam *et al.* (2020) for Bangladesh, and Sharma and Newman (2018) for India. In Jakarta, the GOS proximity showed a limited correlation with the determinants influencing visitation, as highlighted by Setiowati *et al.* (2023) in their work and in alignment with the findings of Yen *et al*. (2017) for Cambodia. The results contrasted the conclusions of Andersson *et al.* (2019) and Honey-Rosés *et al.* (2020), emphasizing the significance of accessibility related to user perceptions and visitation. This can be attributed to the culture of walking and the negative perceptions of dense vegetation among the public. Green space preferences vary between regions due to differences in quantity and quality, historical land use roles, attitudes, perceptions, and cultural contexts of communities. Different perceptions or preferences for ecosystem services are reflected in the willingness to pay for land units, which reflects the value of green spaces. Meanwhile, the positive externality of parks and urban forests on surrounding land prices depends on the community quality and utilization. The analysis of buffer zones can be a meaningful approach for assessing green spaces related to hedonic prices. The manifestation of the GOS value inherent in land prices serves the dual purpose of conferring benefits not just on private sector enterprises through the augmentation of returns on investments in residential or commercial ventures, but also offering substantive impetus to the overarching trajectory of urban economic expansion. The capitalized value in the land market benefits developers or private parties by allowing them to gain profits from housing or commercial development and urban planners and policymakers through strategic efforts of developing adequate and high-quality public green space provisions. The study findings contribute to the design of scenarios for development, including housing construction. Analyzing the impacts as a source of information through the land market allows an examination of the spatial heterogeneity of preferences. This information is valuable for urban planners when considering the social value of green spaces. Future urban landscape designs should analyze the relationships in different scales (e.g., city level versus sub-district level). Understanding the heterogeneity of public preferences provides additional information that assists local governments in determining land prices. The findings have important implications for land use planning and public investment in Jakarta considering that green spaces compete with other land uses. The conservation of open spaces should be a pivotal consideration in urban planning decisions to augment environmental, cultural, and economic values as part of a broader strategy addressing societal concerns (Dahal *et al.,* 2019). Accurate information on the monetary estimation of green spaces can assist policymakers in maximizing the well-being of the community and in developing attractive public investments. These indirect benefits attract the attention of local governments and stakeholders, encouraging them to formulate more effective strategies for the conservation and development of green spaces in budget allocation and urban planning. This study provides important steps in measuring the total benefits of GOS and analyzes interesting implications, such as increased tax revenue for local governments from specific GOS categories. The collaboration between local governments and the private sector aids in developing a property database system, including owner information as a data source for HPM studies. The presence of GOS provides diverse ecosystem services. Public preferences vary based on socio-demographic factors, which have different policy implications. Future studies can focus on the development of a more comprehensive HPM model by considering more variable factors and including more empirical analyses. The findings also recommend further study for analyzing the differences in the GOS categories and sizes driving positive externalities, depicting the "capitalization" of GOS land for property or nearby land value enhancement. This is in line with the results of Franco and Macdonald (2018), who showed a strategic role in the urban economy of developing countries,

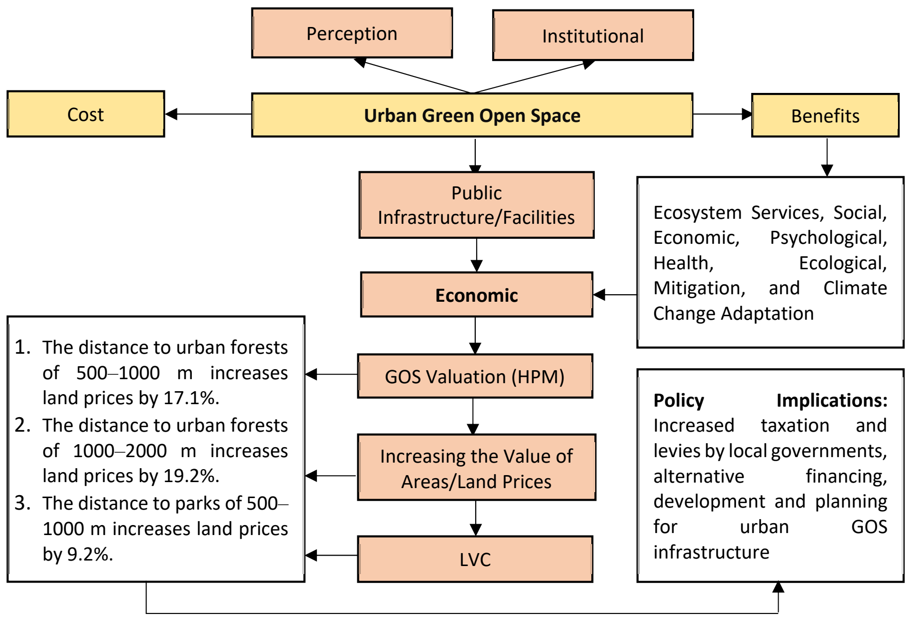

Fig. 5: Policy implications of the urban GOS valuation

particularly in Jakarta. The policy implications must investigate the importance of considering the role and diversity of public preferences regarding development and financing policies, cultural factors, and perceptions (Fig. 5).

The results of this study contribute to understanding urban forests and parks in Jakarta, which have significant impacts on land prices. This work examined the need to consider GOS in land value assessments and urban planning. The implications herein are extended to land use planning and public investments in green spaces, specifically in densely populated areas. Introducing the HPM into the development planning framework can significantly investigate urban planning. This work also acknowledged several limitations, including the limited representation of urban GOS in the Thousand Islands Regency, the sole consideration of land value in the HPM model, and the limited scope of the GOS variables. The generalization of findings to a broader population and other regions was conducted with caution. Future studies must prioritize the development of an exhaustive HPM for Jakarta, including a broader spectrum of the variable factors. This study suggests the need for further investigations to scrutinize nuances within the GOS categories and sizes, elucidating the drivers of positive externalities.

CONCLUSION

This study was conducted as a pioneering effort to use the HPM for the public GOS valuation in Indonesia, consequently establishing a novel and distinctive contribution to the field of urban economics and environmental valuation. The applicability of the HPM model was depicted in Jakarta's mature and privatized land market. The GOS development was found to hold a significant potential in addressing different issues, including environmental justice, public health, and aesthetic and increased land values. GOS effectively enhance climate resilience by providing habitats for biodiversity and supporting the physical and mental well-being of the community through recreational and sports facilities. The concept also creates important externalities in policy design to ensure sufficient presence in urban environments. This study offers valuable insights into the measurement of the benefits of GOS and examines interesting implications, including increased tax revenues for local governments based on specific GOS categories. Effectively developing GOS requires creative thinking to meet the needs of areas with a limited land availability. Moreover, GOS development requires an understanding of how distribution and functionality provide meaning and economic value. Cultural ecosystem services are becoming increasingly important in urban areas facing population growth and challenges. The presence of parks and urban forests increases the land prices by 17.1 and 19.2%, respectively, while cemeteries decrease the variable by −37.6 to −15%. These findings provide policymakers and property developers with valuable information on land transactions and conversion, property development, conservation, and ecologically sound green space network designs. As regards the policy implications suggested, public GOS, such as urban forests and parks, enhance the property values and increase the local tax revenue. Jakarta and other major cities have explored alternative financing through LVC mechanisms to finance the development of urban forests and parks. The land value rate increase can be used as a reference to determine the LVC mechanisms (e.g., imposition of a Beneficiary Zoning Levy), depicting values of 9.2, 17.1, and 19.2% within the affected value area of 500–2000 m. This study did not find statistically significant relationships between the presence of GOS within the 0–500 m radius and land prices in Jakarta, setting it apart from the majority of HPM studies found in the literature, which used Global North countries as their study areas. The analysis of the housing structure variables showed that access to clean water from a public water utility positively influences land prices. Shopping centers, location of the respondents' residences, public high schools, roads within a distance fewer than 200 m, and proximity to CBDs were found to have significant positive coefficients on land prices. By contrast, population density showed a significant negative effect. The presence of urban forests and parks positively affects the land prices in Jakarta, indicating that residents highly value direct access to green spaces. Conversely, the presence of cemeteries negatively affects land prices, suggesting that the setup is an undesirable facility for land buyers. These results confirmed the importance of considering environmental factors and GOS in land transactions and conversion, property development, conservation, and urban green space design, providing policymakers, property developers, and land use planners with valuable information. Valuing green spaces prevents undervaluation and enhances one's understanding of their benefits, which leads to informed decisions on land use planning and public investment in green spaces. Further studies could explore the sizes of green spaces, social functions, and ecosystem services to deepen understanding on the value of GOS and provide a more comprehensive perspective on planning and management. Larger-scale studies that include a wider range of regions must be conducted to obtain significant relationships in the valuation model using the HPM approach.

AUTHOR CONTRIBUTIONS

R. Setiowati conducted all the experiments, wrote the manuscript, and was the corresponding author. R.H. Koestoer as the corresponding author, participated in the interpretation of the results and revised the manuscript, and R.D. Andajani revised the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
CBD	Central business district
COVID-19	Corona virus disease 2019
D	Durbin-watson
DW	Durbin-watson Table
GI	Green infrastructure
GIS	Geographic information systems
GOS	Green open space
ha	Hectare
HPM	Hedonic pricing method
IT	Information technology
JCCG	Jakarta capital city government
km	Kilometers
km^2	Kilometer square
LVC	Land value captured
m	Meter
m^2	Meter square
OLS	Ordinary least squares
people/km^2	People/ square kilometer
R^2	R-squared
RP	Revealed preference
Rp	Rupiah
SD	Standard deviation
SP	Stated preference
SPSS	Statistical package for the social sciences
VIF	Variance inflation factor

REFRENCES

Abdullah, S.; Markandya, A.; Nunes, P.A., (2011). Introduction to economic valuation methods. Res. Tools Nat. Res. Environ. Ecol., 143-187 (**45 pages**).

Abelson, P., (1985). House and land prices in Sydney: 1925 to 1970. Urban Studies, 22(6): 521-534 (**14 pages).**

Alterman, R., (2007). Much more than land assembly: Land readjustment for the supply of urban public services. Analyzing Land Readjustment: Econ, Law, Collect Act. 57-86 **(30 pages).**

Anderson, S.T.; West, S.E., (2006). Open space, residential property values, and spatial context. Reg. Sci. Urban Econ., 36(6): 773-789 **(17 pages).**

Andersson, E.; Barthel, S.; Ahrné, K., (2007). Measuring social–ecological dynamics behind the generation of ecosystem services. Ecol. Appl., 17(5): 1267-1278 **(12 pages)**.

Asadi, S.; Nilashi, M.; Samad, S.; Rupani, P.F.; Kamyab, H.; Abdullah, R., (2021). A proposed adoption model for green IT in manufacturing industries. J. Cleaner Prod., 297: 126629 **(16 pages).**

Artmann, M.; Chen, X.; Iojă, C.; Hof, A.; Onose, D.; Poniży, L.; Breuste, J., (2017). The role of urban green spaces in care facilities for elderly people across European cities. Urban For. Urban Greening., 27: 203-213 **(11 pages).**

Aziz, A.; Anwar, M.M.; Dawood, M. (2021). The impact of neighborhood services on land values: an estimation through the hedonic pricing model. Geo. J., 86(4): 1915-1925 **(11 pages).**

Barbosa, O.; Tratalos, J. A.; Armsworth, P.R.; Davies, R.G., Fuller, R.A., Johnson, P.; Gaston, K.J., (2007). Who benefits from access to green space? A case study from Sheffield, UK. Landscape Urban Plan., 83(2-3): 187-195 **(9 pages).**

Bateman, I.; Department of Transport Großbritannien. (2002). Economic valuation with stated preference techniques: a manual (Vol. 50). Cheltenham: Edward Elgar **(480 pages).**

Belcher, R.N.; Chisholm, R.A., (2018). Tropical vegetation and residential property value: A hedonic pricing analysis in Singapore. Ecol Econ., 149: 149-159 **(11 pages).**

Bertram, C.; Rehdanz, K., (2015). Preferences for cultural urban ecosystem services: Comparing attitudes, perception, and use. Ecosyst Serv., 12: 187-199 **(13 pages)**.

Biao, Z.; Gaodi, X.; Bin, X.; Canqiang, Z.., (2012). The effects of public green spaces on residential property value in Beijing. J Resour Ecol., 3(3): 243-252 **(10 pages)**.

Bockarjova, M.; Botzen, W.J.: Koetse, M.J., (2020). Economic valuation of green and blue nature in cities: A meta-analysis. Ecol Econ., 169: 106480 **(13 pages).**

Boone, C.G.; Buckley, G.L.; Grove, J.M.; Sister, C., (2009). Parks and people: An environmental justice inquiry in Baltimore, Maryland. Ann Assoc Am Geogr., 99(4): 767-787 **(21 pages)**.

Bowler, D.E.; Buyung-Ali, L.; Knight, T.M.; Pullin, A.S., (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landsc Urban Plan., 97(3): 147-155 **(9 pages).**

Brander, L. M.; Koetse, M.J., (2011). The value of urban open space: Meta-analyses of contingent valuation and hedonic pricing results. J Environ Manag., 92(10): 2763-2773 **(11 pages).**

Budiman, A.; Sulistyantara, B.; Zain, A.F., (2014). Detection of greenery open space change of 5 major cities in Java Island (Case study: DKI Jakarta, Bandung City, Semarang City, Jogjakarta City, and Surabaya City). J Lanskap Ind., 6(1): 7-15 **(9 pages).**

Cavailhès, J.; Brossard, T.; Foltête, J.C.; Hilal, M.; Joly, D., Tourneux, F.P.; Wavresky, P., (2009). ;GIS-based hedonic pricing of landscape. Environ Resour Econ., 44(4): 571-590 **(20 pages).**

Central Bureau of Statistics, (2023). Jakarta in numbers 2023 **(935 pages).**

Chiesura, A., (2004). The role of urban parks for the sustainable city. Landscape Urban Plann., 68(1): 129-138 **(10 pages).**

Choumert, J.; Salanié, J., (2008). Provision of urban green spaces: Some insights from economics. Landsc Res., 33(3): 331-345 **(15 pages).**

Czembrowski, P.; Kronenberg, J., (2016). Hedonic pricing and different urban green space types and sizes: Insights into the discussion on valuing eco19system services. Landsc Urban Plan., 146: 11-19 **(9 pages).**

Czembrowski, P.; Łaszkiewicz, E.; Kronenberg, J.; Engström, G.; Andersson, E., (2019). Valuing individual characteristics and the multifunctionality of urban green spaces: The integration of sociotope mapping and hedonic pricing. PloS one., 14(3): e0212277 **(16 pages).**

Daams, M.N.; Sijtsma, F.J.; Veneri, P., (2019). Mixed monetary and non-monetary valuation of attractive urban green space: A case study using Amsterdam house prices. Ecol Econ., 166: 106430 **(12**

pages).

Dahal, R.P.; Grala, R.K.; Gordon, J.S.; Munn, I.A.; Petrolia, D.R.; Cummings, J.R., (2019). A hedonic pricing method to estimate the value of waterfronts in the Gulf of Mexico. Urban For. Urban Greening., 41: 185-194 **(10 pages).**

Engström, G.; Gren, A., (2017). Capturing the value of green space in urban parks in a sustainable urban planning and design context: pros and cons of hedonic pricing. Ecol Soc., 22(2), **(14 pages).**

Franco, S.F.; Macdonald, J.L., (2018). Measurement and valuation of urban greenness: Remote sensing and hedonic applications to Lisbon, Portugal. Reg Sci Urban Econ., 72: 156-180 **(25 pages).**

Freeman, A.M., (1981). Hedonic prices, property values and measuring environmental benefits: a survey of the issues. In Measurement in public choice (pp. 13-32). Palgrave Macmillan, London **(20 pages).**

Fruth, E.; Kvistad, M.; Marshall, J.; Pfeifer, L.; Rau, L.; Sagebiel, J.; Winiarski, B., (2019). Economic valuation of street-level urban greening: A case study from an evolving mixed-use area in Berlin. Land Use Policy., 89: 104237 **(12 pages).**

Gao, X.; Asami, Y., (2007). Effect of urban landscapes on land prices in two Japanese cities. Landscape Urban Plann., 81(1-2): 155-166 **(12 pages).**

Handley, J.; Pauleit, S.; Slinn, P.; Barber, A.; Baker, M.; Jones, C.; Lindley, S., (2003). Accessible natural green space standards in towns and cities: a review and toolkit for their implementation. English Nat. Res. Rep., 526 **(98 pages).**

Hanley, N.; Shogren, J.F.; White, B., (2016). Environmental economics: in theory and practice. Macmillan international higher education **(451 pages).**

Hashim, H.; Ramlan, M.R.; Shiun, L.J.; Siong, H.C.; Kamyab, H.; Abd Majid, M.Z.; Lee, C.T., (2015). An integrated carbon accounting and mitigation framework for greening the industry. Energy Procedia, The 7th International Conference on Applied Energy – ICAE2015 . 75: 2993-2998 **(6 pages)**.

Honey-Rosés, J.; Anguelovski, I.; Chireh, V.K.; Daher, C.; Konijnendijk van den Bosch, C.; Litt, J.S.; Nieuwenhuijsen, M.J., (2021). The impact of COVID-19 on public space: an early review of the emerging questions–design, perceptions and inequities. Cities & health, 5(sup1): S263-S279 **(17 pages)**.

Islam, M.S.; Hossain, R.; Morshed, M.M.; Afrin, S., (2020). The value of environmental (dis) amenities in the urban housing market: evidence from Khulna, Bangladesh. J Urban Manag., 9(2): 180-190 **(11 pages).**

Kabisch, N.; Haase, D., (2014). Green justice or just green? Provision of urban green spaces in Berlin, Germany. Landsc Urban Plan., 122: 129-139 **(11 pages).**

Konijnendijk, C.C.; Annerstedt, M.; Nielsen, A.B.; Maruthaveeran, S., (2013). Benefits of urban parks. A systematic review. A Report for IFPRA, Copenhagen & Alnarp **(70 pages).**

Kong, F.; Yin, H.; Nakagoshi, N., (2007). Using GIS and landscape metrics in the hedonic price modeling of the amenity value of urban green space: A case study in Jinan City, China. Landsc Urban Plan., 79(3-4): 240-252 **(13 pages).**

Khoshnava, S.M.; Rostami, R.; Zin, R.M.; Kamyab, H.; Abd Majid, M.Z.; Yousefpour, A.; Mardani, A., (2020). Green efforts to link the economy and infrastructure strategies in the context of sustainable development. Energy, 193: 116759 **(28 pages).**

Larson, E.K.; Perrings, C., (2013). The value of water-related amenities in an arid city: The case of the Phoenix metropolitan area. Landsc Urban Plan., 109(1): 45-55 **(17 pages).**

Law, (2007). The Law No. 26 of 2007 of the Republic of Indonesia **(107 pages).**

Lewis, B.D., (2007). Revisiting the price of residential land in Jakarta. Urban Stud., 44(11): 2179-2194 **(16 pages).**

Li, S.; Jiang, Y.; Ke, S.; Nie, K.; Wu, C., (2021). Understanding the effects of influential factors on housing prices by combining extreme gradient boosting and a hedonic price model (XGBoost-HPM). Land, 10(5): 533 **(15 pages).**

Li, X.; Wang, Y.; Li, J.; Lei, B., (2016). Physical and socioeconomic driving forces of land-use and land-cover changes: A Case Study of Wuhan City, China. Discrete Dyn. Nat. Soc., **(12 pages).**

Ligus, M.; Peternek, P., (2016). Measuring structural, location and environmental effects: A hedonic analysis of housing market in Wroclaw, Poland. Procedia Soc Behav Sci., 220: 251-260 **(10 pages).**

Lutzenhiser, M.; Netusil, N.R., (2001). The effect of open spaces on a home's sale price. Contemp Econ Policy., 19(3): 291-298 **(8 pages).**

Maller, C.; Townsend, M.; Pryor, A.; Brown, P.; St Leger, L., (2006). Healthy nature healthy people: 'contact with nature'as an upstream health promotion intervention for populations. Health Promot Int., 21(1): 45-54 **(10 pages).**

Melichar, J.; Kaprová, K., (2013). Revealing preferences of Prague's homebuyers toward greenery amenities: The empirical evidence of distance–size effect. Landsc Urban Plan., 109(1): 56-66 **(11 pages).**

MEFR, (2012). The guide to forest ecosystem valuation. Ministry of Environment and Forestry Regulation No. 15 **(27 pages).**

Mirkatouli, J.; Samadi, R.; Hosseini, A., (2018). Evaluating and analysis of socio-economic variables on land and housing prices in Mashhad, Iran. Sustain Cities Soc., 41: 695-705 **(11 pages).**

Morancho, A.B., (2003). A hedonic valuation of urban green areas. Landsc Urban Plan., 66(1): 35-41 **(7 pages).**

Nichols, J.B.; Oliner, S.D.; Mulhall, M.R., (2013). Swings in commercial and residential land prices in the United States. J. Urban Econ., 73(1): 57-76 **(20 pages).**

Palmquist, R.B., (2005). Property value models. Handbook of environmental economics, 2: 763-819 **(57 pages).**

Qu, S.; Hu, S.; Li, W.; Zhang, C.; Li, Q.; Wang, H., (2020). Temporal variation in the effects of impact factors on residential land prices. Appl Geogr., 114: 102124 **(9 pages).**

Raymond, Y.C.; Love, P.E., (2000). Measuring residential property values in Hong Kong. Property Prop Manag., **(12 pages).**

Regional Regulation Number 1 of 2012. Jakarta Spatial Planning for the Year 2030 **(291 pages).**

Rosen, S., (1974). Hedonic prices and implicit markets: product differentiation in pure competition. J Polit Econ., 82(1): 34-55 **(22 pages).**

Setiowati, R.; Koestoer, R.H.; Mizuno, K.; Hasibuan, H.S., (2023). Urban green space during the Coronavirus disease pandemic with regard to the socioeconomic characteristics. Global J. Environ. Sci. Manage., 9(3): 589-606 **(18 pages)**.

Setiowati, R.; Mizuno, K.; Hasibuan, H.S.; Koestoer, R.H., (2022)[a]. Urban green spaces for support healthiness in Jakarta during the COVID-19 pandemic: a quantitative study. Environ. Eng. Res., 28(2): 210598 **(8 pages).**

Setiowati, R.; Mizuno, K.; Hasibuan, H.S.; Koestoer, R.H., (2022)[b]. Actor-network theory approach for urban green spaces planning: Study in Jakarta Capital City, Indonesia. Kasetsart J Soc Sci., 43(4): 1075-1084 **(10 pages).**

Setiowati, R.; Hasibuan, H.S.; Koestoer, R.H.; Harmain, R., (2019). Planning for urban green area and its importance for sustainability: The case of Jakarta. IOP Conference Series: Earth Environ. Sci., 328(1): 012027 **(7 pages)**.

Setiowati, R.; Hasibuan, H.S.; Koestoer, R.H., (2018). Green open space masterplan at Jakarta Capital City, Indonesia for climate change mitigation. IOP Conf. Ser. Earth Environ. Sci., 200(1): 012042 **(9 pages).**

Sharma, R.; Newman, P., (2018). Does urban rail increase land value in emerging cities? Value uplift from Bangalore Metro. Transp Res Part A Policy Pract., 117: 70-86 **(17 pages).**

Shen, Y.; Karimi, K., (2017). The economic value of streets: mix-scale spatio-functional interaction and housing price patterns. Appl. Geogr., 79: 187-202 **(16 pages).**

Shuvo, F.K.; Feng, X.; Akaraci, S.; Astell-Burt, T., (2020). Urban green space and health in low and middle-income countries: A critical review. Urban For Urban Green., 52: 126662 (15 pages).

Smith, V.K.; Poulos, C.; Kim, H., (2002). Treating open space as an urban amenity. Resour Energy Econ., 24(1-2): 107-129 **(23 pages)**.

Strohbach, M.W.; Haase, D., (2012). Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. Landsc Urban Plan., 104(1): 95-104 **(10 pages).**

Sturm, R., & Cohen, D. (2014). Proximity to urban parks and mental health. J. Mental Health Policy Econ., 17(1): 19 (**12 pages).**

Suparman, Y.; Folmer, H.; Oud, J.H., (2016). The willingness to pay for in-house piped water in urban and rural Indonesia. Pap Reg Sci., 95(2): 407-426 **(20 pages).**

Tagliafierro, C.; Longo, A.; Van Eetvelde, V.; Antrop, M.; Hutchinson, W.G., (2013). Landscape economic valuation by integrating landscape ecology into landscape economics. Environ Sci Policy., 32: 26-36 **(11 pages)**.

Trojanek, R.; Gluszak, M.; Tanas, J., (2018). The effect of urban green spaces on house prices in Warsaw. Int J of Strateg Prop Manag., 22(5): 358-371 **(14 pages).**

Tyrväinen, L.; Miettinen, A., (2000). Property prices and urban forest amenities. J Environ Econ Manage., 39(2): 205-223 **(19 pages)**.

Tyrväinen, L., (1997). The amenity value of the urban forest: an application of the hedonic pricing method. Landsc Urban Plan., 37(3-4): 211-222 **(12 pages)**.

Van Oijstaeijen, W.; Van Passel, S.; Cools, J., (2020). Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. J Environ Manag,, 267: 110603 **(10 pages).**

Waltert, F.; Schläpfer, F., (2010). Landscape amenities and local development: A review of migration, regional economic and hedonic pricing studies. Ecol Econ., 70(2): 141-152 **(12 pages)**.

Wendel, H.E.W.; Downs, J.A.; Mihelcic, J.R., (2011). Assessing equitable access to urban green space: The role of engineered water infrastructure. Environ Sci Technol., 45(16): 6728-6734 **(7 pages).**

Wolch, J.R.; Byrne, J.; Newell, J.P., (2014). Urban green space, public health, and environmental justice: The challenge of making cities ‘just green enough’. Landsc Urban Plan., 125: 234-244 **(11 pages).**

Yen, Y.; Wang, Z.; Shi, Y.; Xu, F.; Soeung, B.; Sohail, M.T.; Juma, S.A., (2017). The predictors of the behavioral intention to the use of urban green spaces: The perspectives of young residents in Phnom Penh, Cambodia. Habitat Int., 64: 98-108 (11 pages).

Yusuf, A.A.; Resosudarmo, B.P., (2009). Does clean air matter in developing countries’ megacities? A hedonic price analysis of the Jakarta housing market, Indonesia. Ecol Econ., 68(5): 1398-1407 **(10 pages).**

Zhang, H.; Chen, B.; Sun, Z.; Bao, Z., (2013). Landscape perception and recreation needs in urban green space in Fuyang, Hangzhou, China. Urban For Urban Green., 12(1): 44-52 **(9 pages).**

Zhong, T.; Chen, Y.; Huang, X., (2016). Impact of land revenue on the urban land growth toward decreasing population density in Jiangsu Province, China. Habitat Int., 58: 34-41 **(8 pages).**

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ORIGINAL RESEARCH ARTICLE

Utilization of personal protective equipment and the hygiene sanitation practices of farmers in the application of pesticides

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ABSTRACT

BACKGROUND AND OBJECTIVES: Pesticides are toxic and dangerous materials requiring good handling. Pesticide exposure highly affects farmers' health, especially spray pesticides, which arise from pesticide residues in food, air, and the environment. This research aims to determine the relationship between behavioral factors in using Personal Protective Equipment and individual hygiene and sanitation of farmers who experience health problems. This study also looks at the predictive value of farmers' behavioral factors regarding health problems.
METHODS: The design of this study is cross-sectional with quantitative research type. This study gathered 91 respondents in Jonggol Village, which has the largest agricultural land in Bogor Regency and with farmers who actively use pesticides. Accordingly, this location has a population at risk of pesticide exposure. This study used questionnaires to obtain information about farmer behavior and health problems. It also used the statistical package for the social sciences application to analyze data based on the chi-square test and multiple logistic regression.
FINDINGS: The bivariate analysis results show a significant relationship between the habit of using personal protective equipment (masks) and farmers' health problems, with a test value of 0.019 and an odds ratio of 4.24. The habit of not using hand protection (gloves) is also significantly related to not showering after farming, with a test value of 0.045 and an odds ratio of 3.61. Meanwhile, the variable habit of using hand protection (gloves) has the highest influence, with a test value of 0.008. Farmers who do not use hand protection are 17.5 times more likely to experience health problems than farmers who use hand protection. Meanwhile, the Logistic Model shows that all variables lack a significant relationship.
CONCLUSION: Based on the overall analysis of the behavior of using personal protective equipment and personal hygiene of farmers, this study suggests increasing synergy between agricultural and health instructors in building awareness of using protective equipment and the correct and appropriate use of pesticides among farmers. In a cross-program and cross-sector manner, agricultural extension workers can explain how to wear protective equipment and use pesticides correctly, while health educators can promote pesticide exposure pathways and preventive measures for pesticide-related diseases. Exploring other factors influencing farmers' willingness to use protective equipment and maintain personal hygiene is also essential, including barriers preventing farmers from behaving well. Good pesticide use behavior will maintain the health of farmers and build the health of farmer families and the surrounding community.

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45	2	8

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INTRODUCTION

Pesticides are used to prevent losses due to pest attacks on plants, improve the quality of agricultural products, and protect fruits to attract consumers (Bernardes *et al.,* 2015; Ehzari *et al.,* 2022; Parsafar *et al.,* 2023). The use of pesticides is seen as a cost-effective, labor-saving, and efficient method of pest control and agricultural production. Pesticide consumption is estimated at more than five billion kg annually (FAO/WHO, 2014). However, serious concerns arise regarding the health impacts on farmers due to pesticide exposure, especially spray pesticides arising from residues in food and water, both in the long and short term through the food chain (Zhang *et al*., 2017). Non-target creatures, food chains, and biodiversity can be affected, posing profound dangers to human health and the environment (Samimi *et al.,* 2023). The FAO/WHO (2014) report states that pesticides poison 43 percent (%) of the Zimbabwean population, 25% of the Mexican population, and 23% of Indian farmers and agricultural workers. In several European countries, pesticides are also known to have a negative impact on the health of farmers and vulnerable groups such as pregnant women (Liu *et al.*, 2023). Several countries in Asia have found health problems among farmers who actively use pesticides (Xu *et al*., 2023). Pesticide exposure can occur in every individual. Farmers and agricultural workers are the groups most at risk due to pesticide exposure and additional workplace exposure risks (Balasha *et al*., 2023). ILO (2013) reports that yearly, many agricultural workers and farmers are injured or sick. Approximately 25 million farmers and agricultural workers experienced moderate pesticide poisoning, and three million farmers and agricultural workers experienced severe pesticide poisoning, resulting in approximately 180,000 deaths among agricultural workers in rural areas in developing countries. This condition is caused by wrong perceptions, lack of knowledge, education, law, and unintentional implementation errors (Ali *et al*., 2020). Pesticides, heavy metals (Samimi, 2024) and other toxic compound can pollute agricultural environments such as water, soil, and air, impacting local communities through inhalation, skin, and mouth (Liu *et al*., 2023; Samimi and Nouri, 2023). Previous research found that pesticide poisoning in agricultural workers can cause acute illness (Al-Dawood *et al*., 2023) such as severe headaches, dizziness, skin and eye irritation, coughing, and rhinitis (Koussé *et al*., 2023). Pesticide exposure can also cause chronic diseases such as cancer (Ali *et al*., 2020), leukemia, and brain tumors (Koussé *et al*., 2023). The farmers' use of pesticides requires attention in the area of risk management. Farmers must use personal protective equipment (PPE) according to the Pesticides Commission's standard procedures, including masks, gloves, foot protectors, and protective clothing. Farmers must wear masks to minimize exposure to pesticides that enter the body through the air. The types of masks that can be used are ordinary, surgical, and Non-oil 95 (N95). N95 masks filter smaller particles more than surgical masks. However, the mask must be changed every 8 h because if worn for too long, the filtered particles will accumulate on the mask. Consequently, the former will prevent the latter from functioning optimally. Farmers should also maintain personal hygiene by cleaning themselves immediately after spraying pesticides to reduce the risk of exposure to pesticide particles. Good personal hygiene means washing your hands and showering immediately after mixing and spraying pesticides. Indonesia now has coercive regulations to encourage farmer compliance in agricultural activities through the Law of the Republic of Indonesia no. 22 of 2019 concerning sustainable agricultural cultivation systems. This regulation prohibits agricultural cultivation methods threatening human health, safety, and the environment. Indonesian farmers face risks from using toxic chemical pesticides with application techniques that do not comply with regulations, inadequate spraying equipment that lacks appropriate personal safety equipment, and the frequent reuse of old pesticide containers (Garcia *et al*., 2012). Based on a review of previous reports, analytical research is extremely important to determine the determinant and dominant factors that influence farmers' health based on PPE. Meanwhile, previous research generally focuses on the level of pesticide residue contamination (Khatun *et al.,* 2023), perceived health impacts (Ssemugabo *et al*., 2023), type of pesticide residue (Atnafie *et al*., 2021), and self-descriptive use of protective equipment (Kangkhetkron and Juntarawijit, 2021). Thus, a research gap exists in analyzing the causal relationship between exposure to specifications and disease incidence in farmers. This study aims to determine the relationship between behavioral factors in using PPE and the hygiene and sanitation of individual farmers who experience health problems. This study also aims to determine the most dominant determinants influencing potential health problems in farmers. Bogor City is one of the agricultural areas in Indonesia. Meanwhile, Jonggol Village is one of the sub-districts under the administrative area of Bogor City. Based on preliminary research conducted in Jonggol Village, most farmers experienced health problems and low use of PPE and sanitation. Thus, this study was conducted in Jonggol Village, Indonesia, in 2023.

MATERIALS AND METHODS

The population of this study covers all areas with agricultural areas in Jonggol District, Bogor Regency. Jonggol District consists of 14 villages, namely Sukajaya, Sukagalih, Sukanegara, Weninggalih, Cibodas, Sukamanah, Singasari, Sukamaju, Singajaya, Jonggol, Sukasirna, Bendungan, Balekambang, and Sirnagalih Villages (Fig. 1). This study uses a cross-sectional and quantitative research design. The sample area is the village with the most extensive agricultural land in Jonggol District, namely Jonggol Village. This village has agricultural land covering an area of 833 hectare (ha). Farmers in Jonggol Village are users of triazole pesticides, thereby rendering them vulnerable to pesticide exposure.

Research site

This study starts from the preparation of the proposal and ends with the results report. The study location is centered on the location used by farmers to carry out farming activities and spray pesticides. The sample region or sample area is the village with the largest agricultural land area in Jonggol District. The village is Jonggol Village, with an agricultural land area of 833 ha. The largest village, namely Jonggol Village, was chosen after discovering that farmers use triazole pesticides and based on the focus of the study. This study uses a non-probability sampling technique, which means that not all elements in the population have the same chances of becoming the desired sample. The sample in this study only

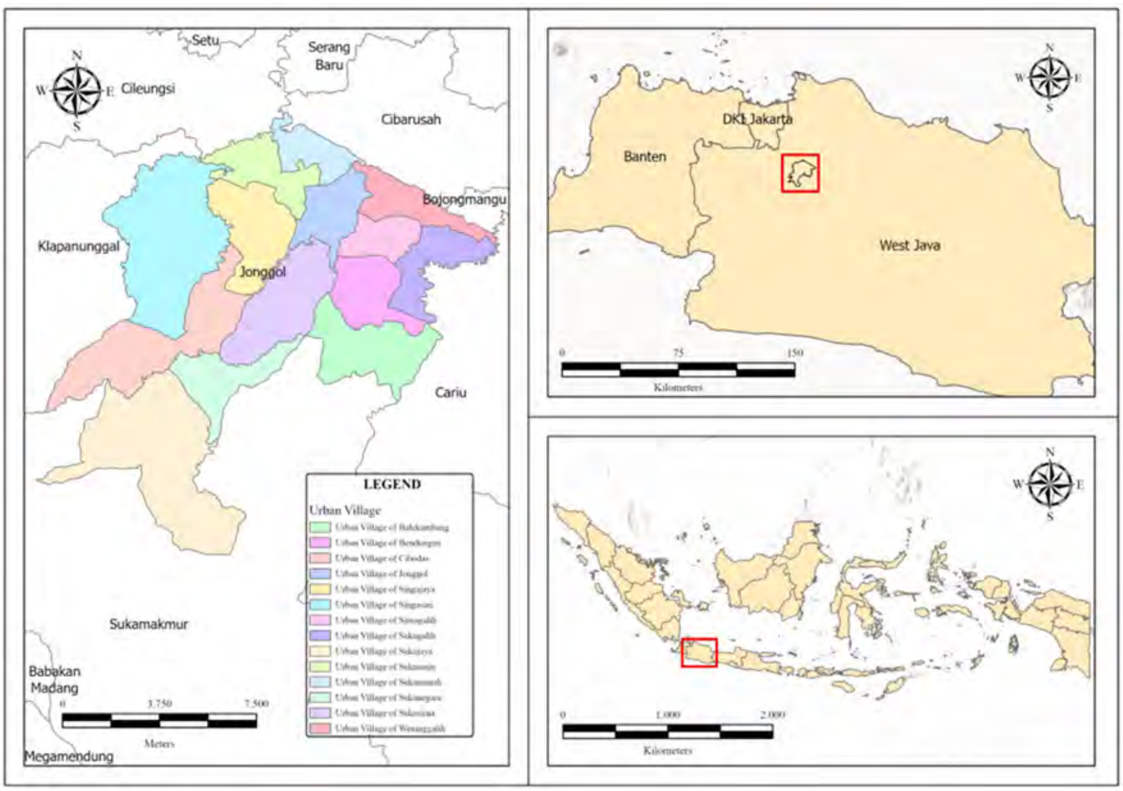

Fig. 1: Geographic location of the study area in the agricultural residential area of Jonggol Village of Jonggol Sub-District in Indonesia

comprised farmers because they are the group most at risk of exposure to pesticide residues. Farmers spend quite a long time in agricultural areas in their daily lives when spraying or applying pesticides to their crops. Thus, they are likely exposed to pesticide residues. Researchers used the Slovin formula to determine the sample size because the number must be representative in taking samples. Thus, the study results can be generalized. The Slovin formula is used for determining a sample of farmers as in Eq. 1 (Jamil *et al*., 2023).

$$n = \frac{N}{1 + Ne^2}, \quad (1)$$

where
n = Total of samples taken for research
N = Total farming population by village
e = Degree of tolerance for inaccuracy in retrieval sample

The study uses a tolerance level of 10%. Thus, the sampling calculation is performed using Eq. 2 (Jamil *et al*., 2023).

$$n = \frac{n}{1 + 975(0.01)^2} = 90.69 = 91 \text{ farmers} \quad (2)$$

Survey

This study first conducted preliminary research to collect initial information regarding the research location. Preliminary research involved ten Jonggol Village farmers in the interview process. Interview results show that 8 out of 10 farmers have worked as farmers for more than ten years. The majority of farmers experience respiratory and digestive health problems. The PPE used is incomplete. At most, farmers use three types of PPE, namely masks, gloves, and protective clothing. Farmers generally shower after spraying pesticides. The results of this interview were then used as material for consideration in preparing the research instrument. This study uses a questionnaire instrument to survey farmers in selected research locations. The questionnaire consists of 1) respondent identity, such as gender, age, and education level; 2) history of working as a farmer; 3) use of personal protective equipment such as masks, gloves, and protective clothing; 4) sanitary hygiene, such as showering after using pesticides; and 5) farmer health problems such as complaints of illness in the last year, both respiratory and digestive health problems (Table 1).

Based on Slovin's calculations, the number of samples in the study was 91 lowland rice farmers. All samples are farmers from Jonggol Village, the group most at risk of exposure to pesticides because they consume raw water sources in agricultural areas and carry out pesticide spraying and mixing activities. This study uses a non-random sampling technique, namely quota sampling. This study only took a

Table 1: Study questionnaire

Questions	
Respondent identity	
Sex	Male or female
Age (year)	26–65; ≥66
Education level	Elementary school (Sekolah dasar/SD); Junior high school (Sekolah menengah pertama/SMP); Senior high school (Sekolah menengah pertama/SMA); Bachelor's Degree (Strata 1/S1)
History of working as a farmer	
How long have you worked as a farmer?	Over 10 years; between 5 and 10 years
Use of PPE	
Do you wear a mask when spraying pesticides?	Yes or no
Do you wear gloves when spraying pesticides?	Yes or no
Do you wear long clothes when spraying pesticides?	Yes or no
Sanitation hygiene	
Do you shower immediately after spraying pesticides?	Yes or no
Farmers' health problems	
Have you had any complaints of illness during the last year?	Yes or no
Do you have respiratory health problems?	Yes or no
Do you have digestive health problems?	Yes or no

sample of farmers because they are the "population at risk" for exposure to pesticides due to their pesticide spraying activities, mixing pesticides, and presence in locations where pesticide residues may remain around the farm. The inclusion criteria for the sample of farmers are willing to be a respondent, able to communicate well, farmers who have worked permanently for more than one year, farmers who spray pesticides, and farmers who mix pesticides. Meanwhile, the exclusion criteria for the sample of farmers are farmers who work as a side job, absent in the target location after three visits, and farmers who do not spray mix pesticides.

Analysis procedures

This study uses a questionnaire instrument that contains demographic characteristics, behavior toward using PPE, behavior toward maintaining personal hygiene and sanitation, and farmers' identified health problems, including digestive and respiratory disorders. The process of obtaining additional data not only happens through interview methods but also observation and documentation regarding farmer behavior in Jonggol Village. From March to April 2022, data were collected through direct field surveys using open and closed questionnaires. This study screened respondents by meeting the research inclusion criteria. The purpose of the study will be explained to selected potential respondents. If the prospective respondent agrees to participate in this study, such respondent will sign an informed consent. All samples in this study have signed informed consent.

Data collection

This study uses two types of data, namely primary and secondary. Primary data in this study are data from interviews with farmers. Primary data are a data source directly provided to data collectors. Secondary data in this study consist of data on the number of farmers and the area of rice farming areas in Jonggol Village obtained from the Central Statistics Agency of Jonggol District, the Bogor Regency Agriculture, Plantation and Forestry Service, the Bogor Regency Health Service, and the Food Crop Protection Center and Horticulture of West Java Province (BPS Kota Bogor, 2021). Two field researchers contacted potential respondents at the farmer group head center and surrounding areas to explain the research objectives and thereafter obtain approval. After obtaining their consent to participate in survey activities, 91 respondents received questionnaires which were distributed using the convenience sampling method. Data collection through surveys is then carried out on site. Table 2 presents the details of the data collection for this study.

Statistical analysis

Data analysis is carried out after passing the processing data stage into information. The information obtained is used for the decision-making process. The entire data processing and analysis process uses SPSS software. Data processing is achieved through the following four steps: editing, coding, data entry, and data cleaning. The collected data then go through a descriptive analysis or univariate analysis process to determine the type of data distribution. Meanwhile, to determine the distribution of data, this study uses a normality test to detect the distribution of data. Normally distributed data must meet the test value of more than 0.05 (p-value > 0.05). Next, bivariate analysis was carried out to determine the relationship

Table 2: Data collection

Content	Jenis data	Methods	Sources	Descriptions
Demographic characteristics of farmers in Jonggol Village	secondary	Document analysis	BPS Kota Bogor	Data on the number of farmers and the area of rice farming in Jonggol Village
Respondent identity	Primary	Questionnaire	Respondents	Gender/age/education level
History of working as a farmer	Primary	Questionnaire	Respondents	How long the respondent has been a farmer in years
Use of PPE	Primary	Questionnaire	Respondents	Wear masks, gloves, and protective clothing when spraying pesticides
Sanitation hygiene	Primary	Questionnaire	Respondents	Bathing after spraying pesticides
Farmers' health problems	Primary	Questionnaire	Respondents	Complaints of illness in the past year, history of respiratory and digestive problems

between the dependent and independent variables. The dependent variable is health problems, while the independent variable is farmers' behavior toward using PPE and sanitation. Logistic regression analysis is also relevant to analyze the direction and correlational relationships because this study focuses on theory development. Logistic regression analysis does not require a solid theoretical basis. Accordingly, such analyses may be suited for theory development. The study hypotheses are as follows:

Hypothesis 1: A relationship exists between the habit of not using mouth/face protection (masks) and the emergence of health problems.

Hypothesis 2: A relationship exists between the habit of not using hand protection (gloves) and the emergence of health problems.

Hypothesis 3: A relationship exists between the habit of not using protective clothing and the emergence of health problems.

Hypothesis 4: A relationship exists between the habit of not bathing after farming and the emergence of health problems.

RESULTS AND DISCUSSION

The latitude of Jonggol village is -6.479789, and the longitude is 107.045101. This village is located 100 m above sea level and has a tropical rainforest climate with rainfall of 30 m3. The boundaries of Jonggol are Sukamanah to the north, Sukasirna to the south, Sirnagalih to the east, and Sukamaju to the west. The land use is 833 ha for rice fields, 180 ha for fields/fields, and 2,360 ha for residential areas. Jonggol has a yard area of 580 ha, a plantation of 3,250 ha, and public facilities of 670 ha. Jonggol Village has a water and river irrigation system and healthy water (groundwater) close to agricultural activities. The majority of residents work as farmers in Jonggol Village. Agricultural activities in the Jonggol Village location still actively use pesticides. Farmers and residents living in the Jonggol Village location are at risk of contamination by pesticide exposure from drinking water sources around the agricultural area. Farmers in Jonggol Village have a community called, POKTAN "Farmers' Group." Among them are the Harapan Tani Farmers Group and the Guyub Tani Farmers Group. Most farmers in Jonggol Village work as rice farmers and carry out rice planting activities for 900 days. Agricultural activities start in April. The first week is the essential fertilization time. Fifteen days after the first fertilization activity, the second fertilization activity is carried out. After 35 days, it is continued with the third fertilization activity. Along with fertilization activities, farmers in Jonggol Village are also actively spraying pesticides to reduce the risk of damage to rice plants by leafhoppers by using fungicides and pesticides. Farmers in Jonggol Village most often use fungicides with the "E-Score" label or brand. The majority of farmers are also active in mixing pesticides. Farmers in Jonggol Village use phosphate, nitrite, nitrate, and MPK fertilizers. Some farmers who work in Jonggol Village also have other activities apart from farming, and some have businesses as fishing owners, trade, and businesses by owning stalls.

Farmers' demographic characteristics in Jonggol Village

Table 1 shows that 93.4% of respondents were male, 6.6% were female, 82.4% had an age range of < 26–65 years, and 17.6% had an age range of more than or equal to (≥) 66 years. Farmers who have their last level of education at SD account for 89%, 5.5% of workers in the tourism sector have their last level of education at SMP, 4.4% of farmers have their last level of education at SMA, as many as 1.1% of farmers have the last level of education at Bachelor's Degree. The dominant farmers have worked as farmers for over ten years, namely 95.6% (87 farmers), and 4.4% of farmers work long term for 5 to 10 years. The characteristics of the farmers in this study align with the study of Li *et al*. (2023), who found that most farmers were men and, on average, had worked as farmers for more than ten years (Zuo *et al*., 2023). Males have more physique and muscle mass tan women, making it possible to carry out farming activities such as hoeing, lifting crops, and digging the soil. Women focus on homemaking and looking after their children at home. Farmers have been working for over ten years for the following reason: on average, farmers are land owners and managers of their crops which explain the urge to work as farmers for a long time. Similar research also reveals that farmers range from productive to old age (Malaj *et al*., 2020). In rural areas, people of productive age who remain physically strong will work professionally. Elderly farmers will only monitor and evaluate the process of managing agricultural land and crop yields.

This study found that 78% of farmers in Jonggol Village experienced health problems due to pesticide use (Table 3). Its results align with previous research, which found that 71.4% of farmers were aware of the emergence of health problems (Alex *et al*., 2018). However, The research of Edwin *et al.* (2021) produced the following contrasting finding: 60% of farmers stated that they did not experience health problems. In another research, Edwin *et al.* (2021) found that of the 40% of farmers who admitted to experiencing health problems, more than 50% experienced respiratory problems. The findings of Edwin *et al*. (2021) are in line with research that the majority of farmers (74.7%) experience respiratory health problems (Table 3). Improper use of pesticides can cause potential respiratory health problems such as asthma, chronic bronchitis, coughing, and shortness of breath; additionally, 20% experience chest tightness (Priyadharshini *et al.,* 2017). This study also found that 44% of farmers experienced digestive health problems (Table 3). This finding aligns with the research by Tambo *et al*. (2020), who found that farmers who did not use PPE experienced digestive disorders such as nausea/vomiting, stomach cramps, and diarrhea.

Univariate analysis description of farmer behavior and health issues

Farmers in Jonggol Village had PPE at their farming headquarters during the interview and observation process. The PPE used includes protective clothing, face protection (mask), and hand protection (gloves). Some farmers do not use PPE when farming, mixing, or spraying pesticides. Farmers are also not good at maintaining personal hygiene. Table 2 shows that more than 80% of farmers do not generally use PPE. The proportion of farmers who do not use PPE is more significant than in the research by Hashemi *et al.* (2012), who found that 60% did not use PPE when using pesticides. This study found that 83.5% of farmers did not wear mouth/face protection (masks). This finding aligns with previous research by Edwin *et al*. (2021), who found that 86.67% of farmers did not use masks, as well as the research by Priyadharsini *et al*. (2017) with a proportion of 80%. Meanwhile, the proportion of farmers who did not use gloves reached 94.5%. Previous research also found that all farmers did not use hand protection (Edwin *et al*., 2021). Meanwhile, the research by Priyadharsini *et al*. (2017) found a more significant proportion of farmers who do not use gloves at 69%. The proportion of farmers who do not use protective clothing is 87.9%. This study aligns with Yuantari *et al*. (2015), who found that all farmers did not wear protective clothing and wore the same clothes for more than one day without washing them. However, the research of Priyadharsini *et al.* (2017) yields the following different finding: 65% of farmers wear unique clothing when working with pesticides; farmers who have the habit of cleaning or showering after planting account for 87.9%. This finding aligns with the research by Edwin *et al.* (2021), who found that most farmers (76.67%) showered and changed clothes after spraying pesticides. Findings related to using PPE when spraying pesticides may be related to knowledge factors that motivate or inhibit farmers' desire to use PPE. Shalaby *et al.* (2022) stated that 4.7% of farmers have limited formal education and have never attended technical training on pesticide safety. These two factors prevent farmers from understanding the dangers of warnings on pesticide labels and instructions for avoiding diseases caused by pesticides. In addition, 15.3% of farmers in this study were illiterate (Shalaby *et al*., 2022). Aspects of farmers' perceptions of pesticides are also aspects that hinder or encourage the implementation of

Table 3: Farmer characteristics in Jonggol Village in 2022

Farmers characteristics	Categories	Number (person)	Percentage (%)
Sex	Male	85	93.4
	Female	6	6.6
Age (year)	26–65	75	82.4
	≥66	16	17.6
Education level	Primary education (SD)	81	89
	Secondary education (SMP)	5	5.5
	Secondary education (SMA)	4	4.4
	Bachelor's degree (S1)	1	1.1
Length of work	Over 10 years	87	95.6
	Between 5 and 10 years	4	4.4

Table 4: Utilization of PPE and sanitary hygiene for farmers in Jonggol Village in 2022

Farmer Behavior Utilizing PPE and Sanitation Hygiene	Categories	Number (person)	Percentage (%)
Habit of not utilizing mouth/face protection (mask)	Yes	76	83.5
	No	15	16.5
Habit of not utilizing hand protection (glove)	Yes	86	94.5
	No	5	5.5
Habit of not utilizing protective clothing	Yes	80	87.9
	No	11	12.1
Habit of not bathing after farming	Yes	11	12.1
	No	80	87.9

Table 5: Farmers' health issues in Jonggol Village in 2022

Farmers' health issue	Categories	Number (person)	Percentage (%)
Emergence of farmer health issues	Yes	71	78
	No	20	22
Experiencing respiratory health issues	Yes	68	74.7
	No	23	25.3
Experiencing digertive health issues	Yes	44	48.4
	No	47	51.6

behavior to prevent pesticide exposure among farmers. Previous research found that of the three levels of perceived danger of pesticides, namely high, medium, and low, only 16.7% of farmers were found to have rated pesticides as very unsafe and not too dangerous (Hashemi *et al.,* 2012). In other words, most farmers do not think that pesticides can harm farmers. Research by Cabasan *et al*. (2019) also found that 38% of farmers consider pesticides the easiest way to control agricultural pests. Other research also found that the inconvenience of using PPE and additional costs were the main reasons for not using PPE (Lari *et al.,* 2022). This study found that using face shields (masks) was associated with health problems (Table 4). The variable habit of using mouth/face protectors (masks) has an odd ratio (OR) value of 4.24, which means that farmers who lack the habit of using mouth/face protectors (masks) will have a risk of experiencing health problems 4.24 higher than farmers who have the habit.

The results of the bivariate test become an indicator for variable selection, which is continued in the logistic regression test. The requirements for variables that will be included in the model for logistic regression testing are variables with a p-value < 0.25. Then, the analysis is repeated along with other variables that meet the requirements to enter the model. Several variables tested in the chi-square analysis in Table 5 can be included in the requirements for testing logistic regression analysis. A total of 3 variables meet the requirements to be included in the model, namely the habit of wearing face protection (mask), the habit of using hand protection (gloves), and the habit of bathing after farming.

Bivariate and multivariate analysis of farmers

This research also conducted a bivariate analysis between the dependent variable, namely health problems among farmers, and the independent variables, namely the habit of not utilizing mouth/face protection (masks), the habit of not utilizing hand protection (gloves), the habit of not utilizing protective clothing, and the habit of not bathing after farming. The bivariate analysis uses the Chi-square test. The bivariate test results show that three variables have a p-value < 0.05, namely the habit of using mouth/face protection (mask) (p-value = 0.019), the habit of using hand protection (gloves), and the habit of bathing after farming (p-value = 0.045). These three variables are related to farmers' emergence of health problems. The OR value shows the strength or weakness of the relationship between two variables (Table 6).

The study also found that as many as 68% of

Table 6: Results of Chi-Square análisis

Behavior of using PPE and hygiene individual sanitation		Emergence of health issues				Total	OR	p-value
		Yes		No				
		n	%	n	%			
Habit of Not UtilizingMouth/Face Protection (Mask)	Yes	63	82.9	13	17.1	76	4.24	0.019
	No	8	53.3	7	46.7	15		
Habit of Not Utilizing Hand Protection (Glove)	Yes	70	81.4	16	18.6	86	17.5	0.008
	No	1	20	4	80	5		
Habit of Not Utilizing Protective Clothing	Yes	9	81.8	2	18.2	11	1.31	0.548
	No	62	77.5	18	22.5	80		
Habit of Not Bathing after Farming	Yes	65	81.3	15	18.8	80	3.61	0.045
	No	6	54.5	5	45.5	11		

farmers experienced respiratory problems due to inadequate behavior in wearing masks. The study finding aligns with the research in Bangladesh that low use of PPE will increase the risk of farmer poisoning (Ali *et al.,* 2020). Health problems among farmers caused by not using face shields or masks when farming include dizziness, blurred vision, eye irritation, and excessive coughing (Tambo *et al.,* 2020). Not using a protective face mask will increase the potential exposure to toxic pesticide substances by inhalation and can cause tissue damage to the lungs, breathing difficulty, reduction in the body's immune system, and reduction in the health status of farmers and their families (ASTDR, 2017). PPE can protect the respiratory system by filtering toxic pesticide substances, thereby reducing the risk of exposure by inhalation. The study results by Zamora *et al.* (2022) in Mexico found health problems among farmers and farming families caused by not using gloves. The results of this study align with this study, which found a relationship between the occurrence of health problems and farmers' behavior in using gloves. The habitual behavior of using hand protection has an OR of 17.5, which indicates that farmers who lack the habit of using hand protection are 17.5 times more likely to experience health problems than those who use hand protection. The behavior of not using gloves is driven by low awareness of using PPE, including hand protection. The behavior of not using hand PPE (gloves) will increase dermal exposure to toxic pesticide substances and can cause tissue damage to the skin (ASTDR, 2017). The potential danger of exposure to toxic substances will occur when farmers wipe their faces or families with farmers' hands contaminated with pesticides. This behavior can become a chain of transmission of toxic pesticide substances by inhalation or oral use. This study also found that 48.4% of farmers experienced digestive disorders due to their behavior of wearing insufficient hand protection. These results align with previous research that contamination due to pesticide exposure by farmers occurs because one of them is reluctant to wear PPE, one of which is hand protection, resulting in skin contamination (Zhang *et al*., 2023). Toxic substances from pesticides in agricultural activities can be minimized by using PPE, namely hand protectors, thereby reducing the risk of exposure to toxic substances when farmers touch parts of their bodies or families. Most farmers in this study have the habit of wearing protective clothing, but the majority also experience health problems. Based on Table 4, the bivariate analysis results did not find a significant relationship between the habit of using protective clothing and farmers' health problems. The results of this study are in line with studies in several American countries that PPE masks influence exposure to pesticides that cause health problems and are less influenced by protective clothing (Paul and Ritz, 2022). Moreover, PPE use is sufficient with the use of masks, gloves, and boots; therefore, thick protective clothing does not have too much of an impact (Khuman *et al*., 2020). Based on these findings, according to ASTDR (2017), not using PPE thick protective clothing will increase dermal exposure to toxic pesticide substances and can disrupt human skin health. If the farmer meets his family and enters the house, the toxic substance will remain in the farmer's body, which could lead to a chain of transmission of toxic pesticide substances by inhalation or oral ingestion. The study also found that as many as 48.4% of farmers experienced digestive disorders. As many as 44.4% of farmers experienced digestive disorders due to the behavior of wearing protective clothing that was not thick enough; this finding is in line with the research that the use of PPE is essential in reducing exposure to toxic pesticide substances in agriculture (Zuo *et al*., 2023). Another study also found that 43% of farmers who did not wear protective clothing experienced itchy skin, and 25% felt a burning sensation (Okonya and Kroschel, 2015). Lari *et al.* (2022) explained that significant differences exist in pesticide exposure on the skin of the legs and chest; followed by the arms, face, and neck of farmers who have sprayed pesticides without PPE. Potential skin exposure values range from 0.15 to 13.45 µg. Farmers treated with PPE experienced a decrease in actual dermal exposure (ADE), %ADE, and ADEh levels than before using PPE. Thus, PPE use is the main parameter for the safety of pesticide users (Lari *et al*., 2022). Farmers in Jonggol Village are accustomed to wearing protective clothing in every farming activity, such as when spraying and mixing pesticides. This behavior can cause disease problems because wearing protective clothing without using other PPE, such as masks, gloves, and boots, still can potentially cause exposure to pesticides and health problems. Lastly, bathing behavior after farming with an OR of 3.61 shows that those who do not bathe after farming are at risk of experiencing health problems 3.61 times higher than farmers who consistently shower after farming. The results of this study align with the research in China, which found that farmers' hygiene is related to farmers' health, namely good hygiene and sanitation, which reduces the emergence of disease in farming families (Jayasiri *et al*., 2022). Not cleaning oneself can increase farmers' risk of exposure to toxic pesticide substances, which cause health problems (Lan *et al*., 2022). Bathing behavior will clean and remove pesticide chemicals when spraying and mixing pesticides, thereby reducing the dangers of pesticide exposure (Kong *et al*., 2021). Based on these findings, according to the EPA (2017), toxic pesticide substances can stick to clothes or skin by not cleaning the body after farming; such practice will contaminate farmers, and they dermally absorb the toxic substances. The study also found that 48.4% of farmers experienced digestive disorders, which is in line with research in China, namely that personal hygiene sanitation affects the health of farmers and farming families (Rousis *et al*., 2021). The condition of farmers in Jonggol Village who do not clean their bodies after bathing means that toxic substances remaining in their bodies have been absorbed into their skin tissue; thus, they metabolize to poison body tissues. Tiny particles of pesticide substances can also be inhaled by farmers or touched on farmers' bodies so that they can cause contamination. Multivariate analysis shows that the habit of using face protection, hand protection, and showering after planting has a p-value > 0.05; thus, all independent variables in the model are unrelated to farmers' health problems. The significant relationship only occurs if the type of farmer behavior is linked bivariately with the farmer's health problems. Simultaneously, all farmer behaviors are unrelated to farmer health problems (Tables 7 and 8).

This study has limitations in the study. It only focuses on looking at pesticide exposure in humans but not on when pesticides are in the environment. In fact, previous research has found a relationship between the safe use of pesticides and the perception of the dangers of pesticides to the environment, namely 79% of farmers are aware of the impact of pesticides on the ecosystem (Cabasan *et al*., 2019). The impact of pesticides on the environment can affect the concentration of pesticides that enter the human body because pesticides in water or air undergo several changing processes. Looking at the discussion from this study, Jonggol Village should be able to implement risk mitigation, such as implementing technology that can detect and monitor pesticide residues through the use of alginate-chitosan films containing Acetylcholinesterase (ACHe) and Choline Oxidase (ChO). Hermanto *et al.* (2023) developed a biosensor technology with good sensitivity, reproducibility, and stability in detecting

Table 7: Bivariate selection results

Independent variables	P-value	Explanation	Information
Habit of not utilizing mouth/Face protection (Mask)	0.019	Hypothesis 1 accepted	Enter the model
Habit of not utilizing hand protection (Glove)	0.008	Hypothesis 2 accepted	Enter the model
Habit of not utilizing protective clothing	0.548	Hypothesis 3 rejected	Not included in the model
Habit of not bathing after farming	0.045	Hypothesis 4 accepted	Enter the model

Table 8: Results of logistic regression

Independent variables	B	SE	Wald	*p-value*	OR (95%CI)	Explanation
Habit of not utilizing mouth/face protection (Mask)	-0.998	0.859	1.348	0.246	0.369 (0.068–1.986)	Hypothesis 1 rejected
Habit of not utilizing hand protection (Glove)	-2.374	1.583	2.982	0.084	0.065 (0.003–1.446)	Hypothesis 2 rejected
Habit of not bathing after farming	0.783	1.289	0.369	0.544	2.188 (0.175–2.355)	Hypothesis 4 rejected
Constant	4.335	2.257	3.689	0.055	76.319	

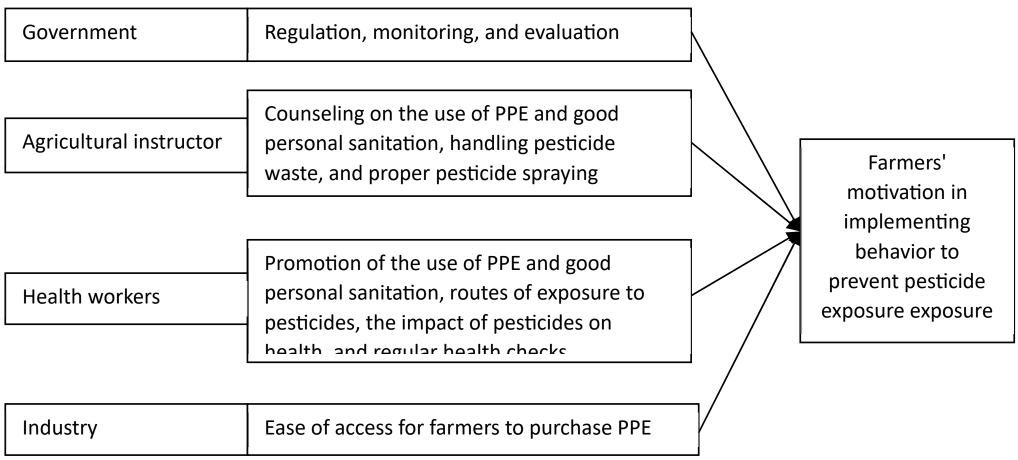

Fig. 2: Relationship between cross-sector roles and farmer motivation in implementing pesticide exposure prevention behavior

and monitoring pesticide residues. This technology is also easy to use, fast, and cheap; moreover, the analysis process can be carried out on site, thereby possibly reducing the barriers for farmers to use PPEs (Hermanto *et al*., 2023). Increasing farmers' awareness and knowledge of using pesticides and PPE and monitoring and evaluating PPE access and availability are both essential for the government, agricultural extension workers, industry, and various agricultural sectors. Health workers can also check the health of farmers and farming families periodically so that future researchers can check pesticide levels in the blood of farmers and farming families or pesticide levels in soil, water, or air as another parameter. Fig. 2 illustrates the interrelationship of the roles between cross-sectors.

CONCLUSION

Based on the study results, 83.5% of farmers did not use mouth/face protection (mask), 94.5% did not use hand protection (gloves), and 87.9% did not use protective clothing. By contrast, most farmers behave well in terms of bathing after planting, namely 87.9%. The habit of not using mouth/face protection (mask) (p-value = 0.246), the habit of not using hand protection (glove) (p-value = 0.084), and the habit of not bathing after farming (p-value = 0.544) are insignificantly related simultaneously in overcoming farmers' health problems. Meanwhile, all three significantly have a spatial influence on farmers' health problems. The habits of not using face protection (mask) (p-value = 0.019), not using hand protection (gloves) (p-value = 0.008), and not showering after planting (p-value = 0.045) have a real impact on farmers' health problems. Farmers who do not use face and mouth protection are 4.24 times more likely to experience health problems than those who do. The behavior of not bathing after farming is 3.61 times more likely to experience health problems than the opposite. The behavior of not using hand protection (gloves) partially has the most vital relationship with the emergence of health problems. Farmers who do not use hand protection (gloves) are

17.5 times more likely to experience health problems than those who use gloves. The habit of not using protective clothing is not related to health problems (p-value = 0.548). As many as 78% of farmers stated that they had health problems, 74.7% experienced respiratory health problems, and 48.4% experienced digestive health problems. These findings demonstrate the importance of in-depth epidemiological studies of specific environmental factors and pesticide exposure pathways that cause farmer health problems. This study has limitations and also guides future research. Although this study discusses the habitual behavior of using PPE, farmer hygiene, and sanitation regarding farmer health problems, this study is limited to one village in West Java Province, namely Jonggol Village. Further research on farmer behavior and health issues should be conducted to assess exposure to environmental pesticides and their toxic substances in the human body, which could contribute to expanding research results. Future research should conduct qualitative studies through in-depth interviews or Focus Group Discussions, which can contribute to increasing the strength of the relationship between farmer health disorders and building the health of farmer families and the surrounding community. Another form of intervention is designing and implementing programs in collaboration with agricultural extension workers, health workers, and local community leaders using a persuasive approach.

AUTHOR CONTRIBUTIONS

G. Fizulmi permorfed the results, prepared the manuscript text, and manuscript edition. H. Agustina performed the data analysis, prepared all the maps and figures, and interpretation of the results.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

>	More than
≥	More than or equal to
<	Less than
%	Percent
%ADE	Percentage of actual dermal exposure
µg	Micrograms
ACHe	Acetylcholinesterase
ADE	Actual dermal exposure
ASDR	Agency for toxic substances and disease registry
ChO	Choline oxidase
e	Degree of tolerance for inaccuracy in retrieval sampel
FAO	Food and agriculture organization
ha	Hectare
km	Kilometer
M	Meter
OR	odd ration
N	Total farming population by village

n	Total of samples taken for research
N95	Non-oil 95 (N95)
PPE	Personal protective equipment
p-value	The probability under the assumption of no effect or no difference
S1	Strata 1 (Bachelor degree)
SD	*Sekolah dasar* (elementary school)
SMA	*Sekolah menengah atas* (senior high school)
SMP	*Sekolah menengah pertama* (junior high school)
SPSS	*Statistical package for the social sciences*

REFERENCES

Al-Dawood, A.; Shawaqfeh, S.; Al-Zyoud, F.; Mamkagh, A.; Al-Atiyat, R.; Hasan, H., (2023). Awareness of pesticides' residues in food and feed among students of the Faculty of Agriculture, Mutah University, Jordan. J. Saudi Soc. Agric. Sci. 1-10 **(10 pages).**

Alex, A.A.; Longinus, N.K.; Olatunde, A.M.; Chinedu, N.V., (2018). Pesticides related knowledge, attitude and safety practices among small-scale vegetable farmers in lagoon wetlands, Lagos, Nigeria. J. Agric. Environ. Int. Dev., 112(1): 81–99 **(19 pages)**.

Ali, M.P.; Kabir, M.M.M.; Haque, S.S.; Qin, X.; Nasrin, S.; Landis, D.; Holmquist, B.; Ahmed, N., (2020). Farmer's behavior in pesticide use: Insights study from smallholder and intensive agricultural farms in Bangladesh. Sci. Total Environ., 747(2020): 141160 **(20 pages).**

ASTDR, (2017). Toxicological Profile for DDT, DDE, and DDD. Agency for Toxic Substances and Disease Registry.

Atnafie, S.A.; Muluneh, N.Y.; Getahun, K.A.; Woredekal, A.T.; Kahaliw, W., (2021). Pesticide Residue Analysis of Khat Leaves and Health Risks among Khat Chewers in the Amhara Region, Northwestern Ethiopia. J. Environ. Public Health. 2021: 4680573 **(8 pages)**.

Balasha, M.; Munyahali, W.; Kulumbu, J.T.; Okwe, A.N.; Fyama, J.N.M.; Lenge, E.K..; Tambawe, A.N., (2023). Understanding farmers' perception of climate change and adaptation practices in the marshlands of South Kivu, Democratic Republic of Congo. Clim. Risk Manage., 39(2023): 100469 **(15 pages)**.

Bernardes, M.F.F.; Pazin, M.; Pereira, L.C.; Dorta D.J., (2015). Impact of pesticides on environmental and human health. IntechOpen **(41 pages)**.

BPS Kota Bogor, (2021). Kota Bogor dalam Angka 2021. BPS, Bogor **(250 pages)**.

Cabasan, M.T.N.; Tabora, J.A.G.; Cabatac, N.N.; Jumao-as, C.M.; Soberano, J.O.; Turba, J.V.; Dagamac, N.H.A.; Barlaan, E., (2019). Economic and ecological perspectives of farmers on rice insect pest management. Glob. J. Environ. Sci. Manag., 5(1): 31–42 **(12 pages)**.

Edwin, T.; Bachtiar, V.S.; Helard, D.; Komala, P.S.; Kusuma, R.N., (2021). Case study: Water resources, knowledge and safety practices of pesticides among farmers around lake diatas of West Sumatera. IOP Conf. Ser. Earth Environ. Sci., 757(2021): 012047 **(8 pages)**.

Ehzari, H.; Safari, M.; Samimi, M.; Shamsipur, M.; Gholivand, M.B, (2022). A highly sensitive electrochemical biosensor for chlorpyrifos pesticide detection using the adsorbent nanomatrix contain the human serum albumin and the Pd: CdTe quantum dots. Microchem. J., 179: 107424 **(10 pages).**

EPA, (2017). EPA Research. Office of Research and Development. United States Environmental Protection Agency. Washington **(36 pages)**.

FAO/WHO, (2014). Pesticide residues in food 2014 - Report 2014. FAO and WHO, Rome **(733 pages)**.

Hashemi, S.M.; Rostami, R.; Hashemi, M.K.; Damalas, C.A., (2012). Pesticide Use and Risk Perceptions among Farmers in Southwest Iran. Hum. Ecol. Risk Assess., 18(2): 456–470 **(15 pages)**.

Hermanto, D.; Ismillayli, N.; Muliasari, H.; Wirawan, R.; Kamali, S.R., (2024). Silver-based plasmonic nanoparticles for biosensor organophosphate pesticides using a single film containing acetylcholinesterase/choline oxidase. Glob. J. Environ. Sci. Manag., 10(1): 1–12 **(12 pages)**.

ILO, (2013). Keselamatan dan kesehatan kerja di tempat kerja: sarana untuk produktivitas. International Labour Organization. Occupational safety and health in the workplace: tools for productivity, Jakarta **(111 pages)**.

Jamil, M.H.; Tika, N.; Fudjaja, L.; Tenriawaru, A.N.; Salam, M.; Ridwan, M.; Muslim, A.I.; Chand, N.V., (2023). Effectiveness of Agricultural Extension on Paddy Rice Farmer's Baubau City, Southeast Sulawesi, Indonesia. Sustainability. 15(4): 3773 **(23 pages).**

Jayasiri, M.M.J.G.C.N.; Yadav, S.; Dayawansa, N.D.K.; Propper, C.R.; Kumar, V.; Singleton, G.R., (2022). Spatio-temporal analysis of water quality for pesticides and other agricultural pollutants in Deduru Oya river basin of Sri Lanka. J. Clean. Prod., 330: 1-11 **(11 pages).**

Kangkhetkron, T.; Juntarawijit, C., (2021). Factors Influencing Practice of Pesticide Use and Acute Health Symptoms among Farmers in Nakhon Sawan, Thailand. I. J. Environ. Res. Public Health. 8(16): 8803 **(12 pages)**.

Khatun, P.; Islam, A.; Sachi, S.; Islam, M.Z.; Islam, P., (2023). Pesticides in vegetable production in Bangladesh: A systemic review of contamination levels and associated health risks in the last decade. Toxicol. Rep., 11(2023): 199–211 **(13 pages)**.

Khuman, S.N.; Vinod, P.G.; Bharat, G.; Kumar, Y.S.M.; Chakraborty, P. (2020). Spatial distribution and compositional profiles of organochlorine pesticides in the surface soil from the agricultural, coastal and backwater transects along the south-west coast of India. Chemosphere. 254(2020): 126699 **(11 pages).**

Kong, X.P.; Zhang, B.H.; Wang, J., (2021). Multiple roles of mesoporous silica in safe pesticide application by nanotechnology: A Review. J. Agric. Food Chem., 69(24): 6735–6754 **(20 pages)**.

Koussé, J.N.D.; Ilboudo, S.; Ouédraogo, J.C.R.P.; Hunsmann, M.; Ouédraogo, G.G.; Ouédraogo, M.; Kini, F.B.; Ouédraogo, S., (2023). Self-reported health effects of pesticides among cotton farmers from the Central-West region in Burkina Faso. Toxicol. Reports, 11(2023): 273–282 **(20 pages).**

Lan, T.; Cao, F.; Cao, L.; Wang, T.; Yu, C.; Wang, F., (2022). A comparative study on the adsorption behavior and mechanism of pesticides on agricultural film microplastics and straw degradation products. Chemosphere, 303(2022): 135058 **(9 pages).**

Lari, S.; Jonnalagadda, P.R.; Yamagani, P.; Medithi, S.; Vanka, J.; Pandiyan, A.; Naidu, M.; Jee, B., (2022). Assessment of dermal exposure to pesticides among farmers using dosimeter and hand washing methods. Front. Public Health. 10: 957774 **(14 pages)**.

Li, H.; Wang, C.; Chang, W.Y.; Liu, H., (2023). Factors affecting Chinese farmers' environment-friendly pesticide application behavior: A meta-analysis. J. Clean. Prod., 409: 137277 **(11 pages).**

Liu, B.; Curls, C.l.; Brantsaeter, A.l.; Torjusen, H.; Sun, Y.; Du, Y.; Lemhler, H.J.; Balentine, A.; Snetselaar, L.G.; Bao, W., (2023). Perspective: Organic food consumption during pregnancy and the potential effects on maternal and offspring health. Adv. Nutr., 14(1): 12–21 **(10 pages).**

Malaj, E.; Liber, K.; Morrissey, C.A., (2020). Spatial distribution of agricultural pesticide use and predicted wetland exposure in the Canadian Prairie Pothole Region. Sci. Total Environ., 718(2020): 134765 **(10 pages).**

Okonya, J.S.; Kroschel, J., (2015). A Cross-Sectional Study of Pesticide Use and Knowledge of Smallholder Potato Farmers in Uganda. Biomed Res. Int., 2015: 759049 **(10 pages)**.

Paul, K.C.; Ritz, B., (2022). Epidemiology meets toxicogenomics: Mining toxicologic evidence in support of an untargeted analysis of pesticides exposure and Parkinson's disease. Environ. Int., 170(2022): 107613 **(14 pages).**

Parsafar, B.; Ahmadi, M.; Jahed Khaniki, Gh.J.; Shariatifar, N.; Rahimi Foroushani, A., (2023). The impact of fruit and vegetable waste on economic loss estimation. Global J. Environ. Sci. Manage., 9(4): 871-884 **(14 pages).**

Priyadharshini, U.K.; Latha, R.; Kavitha, U.; Nirmala, N., (2017). Effects of organophosphorus pesticides on cardiorespiratory parameters among the farmers. J. Clin. Diagnostic Res., 11(9): CC01–CC04 **(4 pages)**.

Rousis, N.I.; Emma, G.L.; Felix, H.; Fransesco, P.; Miguel, M.S.; Ettore, Z.; Sara, C., (2021) Wastewater-based epidemiology as a novel tool to evaluate human exposure to pesticides: Triazines and organophosphates as case studies. Sci. Total Environ., 793: 148618 **(10 pages).**

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4).

Shalaby, S.E.M.; El-Metwally, I.M.; Abou-Ellela, G.M.; Abdou, G.Y., (2022). Occupational Workers Understanding of Pesticide Lables and Safety Practices in Egypt. Egypt. J. Chem., 65(6): 367–380 **(14 pages)**.

Ssemugabo, C.; Bradman, A.; Ssempebwa, J.C.; Guwatudde, D., (2023). Consumer Awareness and Health Risk Perceptions of Pesticide Residues in Fruits and Vegetables in Kampala Metropolitan Area in Uganda. Environ. Health Insights. 17: 11786302231184752 **(8 pages)**.

Tambo, JA.; Mugambi, I.; Onyango, D.O.; Uzayisenga, B.; Romney, D., (2023). Using mass media campaigns to change pesticide use behaviour among smallholder farmers in East Africa. J. Rural Stud., 9(2023)9: 79–91 **(13 pages).**

Xu, Y.; Yang, X.; Chen, D.; Xu, Y.; Lan, L.; Zhao, S.; Liu, Q.; Snijders, A.M.; Xia, Y., (2023). Maternal exposure to pesticides and autism or attention-deficit/hyperactivity disorders in offspring: A meta-analysis. Chemosphere. 313(2023): 137459 **(8 pages).**

Yuantari, M.G.C.; Van Gestel, C.A.M.; Van Straalen, N.M.; Widianarko, B.; Sunoko, H.R.; Shobib, M.N., (2015). Knowledge, attitude, and practice of Indonesian farmers regarding the use of personal protective equipment against pesticide exposure. Environ. Monit. Assess., 187: 142 **(7 pages)**.

Zamora, A.N.; Watkins, D.J.; Peterson, K.E.; Téllez-Rojo, M.M.; Hu, H.; Meeker, J.D.; Cantoral, A.; Mercado-García, A.; Jansen, EC., (2022). Prenatal maternal pesticide exposure in relation to sleep health of offspring during adolescence. Environ. Res., 204: 111977 **(9 pages)**.

Zhang, Q.; Xia, Z.; Wu, M.; Wang, L.; Yang, H., (2017). Human health risk assessment of DDTs and HCHs through dietary exposure in Nanjing, China. Chemosphere. 177: 211–216 **(6 pages)**.

Zhang, G.; Olsson L.R.; Hopkins, B.K., (2023). Strategies and techniques to mitigate the negative impacts of pesticide exposure to honey bees. Environ. Pollut., 318: 120915 **(12 pages).**

Zuo, W.; Lin, Q.; Liu, X.; Lv, L.; Zhang, C.; Wu, S.; Cheng, X.; Yu, Y.; Tang, T., (2023). Spatio-temporal distribution of organochlorine pesticides in agricultural soils of southeast China during 2014-2019. Environ. Res., 232: 116274 **(7 pages).**

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CASE STUDY

Life cycle assessment and life cycle cost of tofu production and its extended recycling scenario

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ABSTRACT

BACKGROUND AND OBJECTIVES: The current literature on tofu production has predominantly focused on exploring the value-added potential of the waste generated during tofu production and conducting impact assessments related to this production. However, a noticeable gap remains in the research concerning the comprehensive examination of life cycle costs and eco-efficiency in tofu production and its associated waste. This study aims to assess the environmental and economic impacts of the implementation of recycling alternatives using a life cycle assessment and life cycle cost approach. The impact of waste recycling on the eco-efficiency of small and medium-sized enterprises in Sugihmanik Village, Grobogan Regency, Indonesia is also examined.

METHODS: To achieve this goal, this study employed life cycle assessment and life cycle cost methodologies to evaluate eco-efficiency. Data were collected through interviews and direct observations. Cradle-to-grave (tofu production) and cradle-to-cradle (tofu production and waste recycling) approaches were compared. Environmental impact was assessed by determining the 12 impact categories. Environmental cost was determined using the eco-cost 2023 method, and environmental and economic impacts were examined with SimaPro software version 9.4.

FINDINGS: Life cycle assessment analysis revealed eutrophication, carbon footprint, and freshwater ecotoxicity to be the categories with the most significant impact for each process. In particular, the eco-cost of the cradle-to-grave approach was 7.03 United States dollars, and that of the cradle-to-cradle approach was 7.90 United States dollars. Life cycle cost analysis yielded a net value of 1.33 United States dollars for the cradle-to-grave process and 38.16 United States dollars for the cradle-to-cradle process. According to the life cycle cost analysis, the recycling scheme increased the overall cost of production. Meanwhile, the eco-efficiency analysis demonstrated an increase in the eco-efficiency of tofu production (cradle-to-grave) and the recycling system (cradle-to-cradle). Waste recycling can increase the eco-efficiency index from 0.18 to 5.

CONCLUSION: Life cycle assessment identified eutrophication, carbon footprint, and ecotoxicity (freshwater) as the three major impact categories. Proper waste management in tofu production offers environmental benefits and significant profits, with the net value of the cradle-to-cradle process at 38.99 US dollars. The eco-efficiency values showed a substantial positive increase, and the waste processing scenarios were found to be sustainable and economically beneficial. These findings suggest new business opportunities through straightforward waste processing and affordable production costs. The scheme also reduces the environmental impact and increases the efficiency and profit of the overall tofu production system.

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41

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INTRODUCTION

Tofu is preferred by Indonesians because of its affordability and abundant protein content (Zheng *et al.*, 2020). As highlighted by Plamada *et al.* (2023), tofu can be used as an alternative to cheese or milk-based products and as a meat substitute food for vegan. Data on the average per capita tofu consumption for 2021 in Indonesia revealed a weekly consumption of 0.3 gram (g), marking a 3.75 percent (%) increase from the preceding year's 0.293 kilogram(kg), (Hulu, 2023). This uptick aligns with the growth of small businesses and the tofu production industry. Hartini *et al.* (2021) emphasized that the surge in tofu enterprises has positive and negative consequences and fosters augmented income and job prospects, particularly in small- and medium-sized enterprises (SMEs) and the tofu production sector (Ratmono *et al.*, 2023). Conversely, the downside is related to the heightened environmental pollution arising from tofu production (Zheng *et al.*, 2020). Byproducts from tofu production are generated in the form of liquid (wastewater) and solid waste. Wastewater is produced during the stages of soaking, mixing, and tofu molding (Hartini *et al.*, 2021). Ajijah *et al.* (2020) reported that this wastewater contains high amounts of proteins (40% – 60%), fats (10%), and carbohydrates (25% – 50%) and has a biological oxygen demand (BOD) of 6,000 – 8,000 mg/L, a chemical oxygen demand (COD) of 7,500 – 14,000 mg/L, and a pH below 6. Solid waste is produced during cooking, filtering, and frying and constitutes approximately 25% – 35% of total tofu production. In SMEs, solid waste can be derived as tofu dregs, which can be converted to residual biomass for fuel (Hartini *et al.*, 2021). Bahri *et al.* (2021) reported that tofu dregs still contain high levels of nutrients, with 23.62% protein, 7.78% fat, and 65% fiber. When appropriately treated, solid waste (tofu dregs) can be used as a viable food ingredient (Xu *et al.*, 2020). In Indonesia, numerous studies have focused on the treatment of waste from tofu production. The Ministry of Environment and Forestry of Indonesia has highlighted diverse waste management strategies, including source reduction, reuse or recycling, and appropriate waste disposal methods (Budihardjo *et al.*, 2022; Kurniawan *et al.*, 2023). Various waste types that retain fibers, fats, proteins, carbohydrates, minerals, and organic acids have the potential to be transformed into alternative products with economic value (Esteban and Ladero, 2018; Samimi and Nouri, 2023). Many investigations have focused on the treatment of wastewater from tofu production to meet wastewater standards. For example, Zunidra *et al.* (2022) used a biofilter enriched with microorganisms in an anaerobic–aerobic system to treat wastewater containing tofu. Other studies explored the conversion of soy whey (Dai *et al.*, 2023) and wastewater (Nugroho *et al.*, 2019) from tofu production to organic fertilizers, biogas, and digestate (Sari *et al.*, 2021). Researchers also explored ways to elevate the economic value of wastewater while curbing its environmental impact. A promising approach is to transform tofu wastewater into nata de soya (Ropiudin and Syska, 2023). Wastewater shows potential in generating high-fiber nourishment for community consumption (Pérez-Marroquín *et al.*, 2023) because it contains sufficient fats, oils, pigments (Saba *et al.*, 2023), proteins, and carbohydrates (Karlović *et al.*, 2020). Diverse applications for process tofu dregs have also emerged, including the production of swollen tempeh (locally known as *tempe gembus*), animal feed, tofu dregs crackers, soy sauce, flour (Dewilda *et al.*, 2023), and fermented foods (Qiu *et al.*, 2022). Syarifuddin *et al.* (2021) explored the possibility of converting tofu dregs into fish feed. Gultom *et al.* (2021) harnessed tofu dregs to craft tissue paper. Waste recycling is always interesting because it is one of the components to achieve a circular economy and can preserve natural resources. Utilizing the byproducts of tofu production will generate sustainable benefits and circularity impact but great challenges (Colimoro *et al.*, 2023). Food safety is one of the main concerns in the recycling of byproducts, even though it may be simple and environmentally friendly (Pushparaj *et al.*, 2022). In an effort to address environmental pollution, SMEs engaged in tofu production are encouraged to broaden their focus beyond economic growth and undertake environmentally sustainable practices. An instrumental method frequently embraced in tackling environmental issues is eco-efficiency (EE). EE denotes the practice of manufacturing goods and rendering services while minimizing resource consumption, energy usage, costs, and waste generation (Al-Shami and Rashid, 2021; Moghadam and Samimi, 2022). It emphasizes the adoption of diverse environmental enhancement strategies that yield value-added advantages for industrial stakeholders (Mendoza *et al*., 2019). Research on tofu production has predominantly focused on assessing its environmental ramifications by employing various methodologies, such as life cycle assessment (LCA) and environmental impact evaluation. Kurniawati *et al.* (2019) assessed the process, waste, and emissions released into the environment, with particular emphasis on global warming potential (GWP). Their findings revealed that manufacturing 1 kg of fresh tofu entailed 1.5269 MJ/kg energy consumption and resulted in the emission of pollutants such as carbon dioxide (CO_2), nitrogen oxide (NO_x), carbon monoxide (CO), and methane (CH_4), culminating in a total of 0.1766 kg of carbon dioxide equivalent (kg CO_2eq). These emissions collectively contribute to the overall potential GWP. Sari *et al.* (2021) conducted similar investigations to scrutinize the environmental implications of tofu production in West Jakarta, Indonesia. Their results underscored the notable environmental impact of tofu production with a substantial GWP value of 0.882 kg CO_2eq, constituting a significant portion of the process' overall 0.978 CO_2eq. Mejia *et al*. (2018) evaluated greenhouse gas (GHG) emissions associated with tofu production and showed that 16% of CO_2eq stems from packaging, 52% from tofu manufacturing, 23% from packaging, and 9% from transportation, collectively contributing to the cumulative emissions linked to the production of 1 kg of packaged tofu. This finding indicates that tofu production has a relatively modest GHG effect. Nevertheless, the economic performance and EE of tofu production and its recycling system has never been analyzed. Mendoza *et al.* (2019) highlighted the significance of life cycle cost (LCC) in bridging environmental concerns with economic strategies. This approach is interlinked with EE, which generates value with a minimal environmental impact throughout the lifecycle of a product. Employing LCC, LCA, and EE can shape strategies for environmental enhancement while prioritizing economic advantages (Budihardjo *et al*., 2023). This viewpoint was supported by Jain *et al.* (2022), who advocated for the confluence of LCC and LCA owing to their complementary nature. Mendoza *et al.* (2019) evaluated economic and environmental benefits in disposable baby diaper production using an environmentally friendly design and revealed an 11% reduction in LCC; EE analysis showed a 7%–170% higher environmental friendliness compared with conventional diapers. Zhang *et al*. (2020) focused on assessing the environmental impact and aiding financial decision-making in PET bottle recycling for blanket production in China and demonstrated that replacing coal with natural gas will significantly reduce environmental impacts and economic burdens. Smith and Lal (2022) investigated the environmental and economic implications of apple juice production in the Northeastern United States and found that the 100% on-site distribution scenario exhibited the lowest carbon footprint at 0.91 kgCO_2eq and 2.31×10^{-3} kg nitrogen oxide equivalent ((NO_x)eq) per 12 ounces of apple juice portion, making it the most cost-effective approach that features a mere USD 1.43 per product while considering capital, fixed, operational, and environmental costs. The integration of LCA and LCC can be used for a comprehensive evaluation of the product lifecycle; however, its role in achieving eco-efficiency in the tofu industry is not yet understood. Drawing upon the outlined challenges and the existing research landscape, this study integrates LCC, LCA, and EE to comprehensively evaluate the economic and environmental aspects of solid and wastewater management in tofu production. The primary goal is to cultivate the development of a circular economy within SMEs operating in the tofu production sector of Sugihmanik Village in Grobogan Regency, Indonesia. The first objective is to assess the environmental impact of tofu production and its recycling alternatives using an LCA approach. The total costs required for waste recycling are estimated using the LCC approach. With Sugihmanik Village as a case study, this research analyzes the impact of waste processing on the enhancement of eco-efficiency in SME tofu production enterprises. By combining these three objectives, this study provides a holistic understanding of the environmental impact, costs, and efficiency of waste processing in tofu production enterprises in Sugihmanik Village. The study was conducted in Sugihmanik Village, Graimobogan Regency, Central Java Province, Indonesia in 2023.

MATERIALS AND METHODS

Several steps were taken to achieve these study aims. Data were collected for LCA and LCC calculations. The LCA for the tofu production and extended scenario consists of several steps, including goal and scope definition, life cycle inventories, life

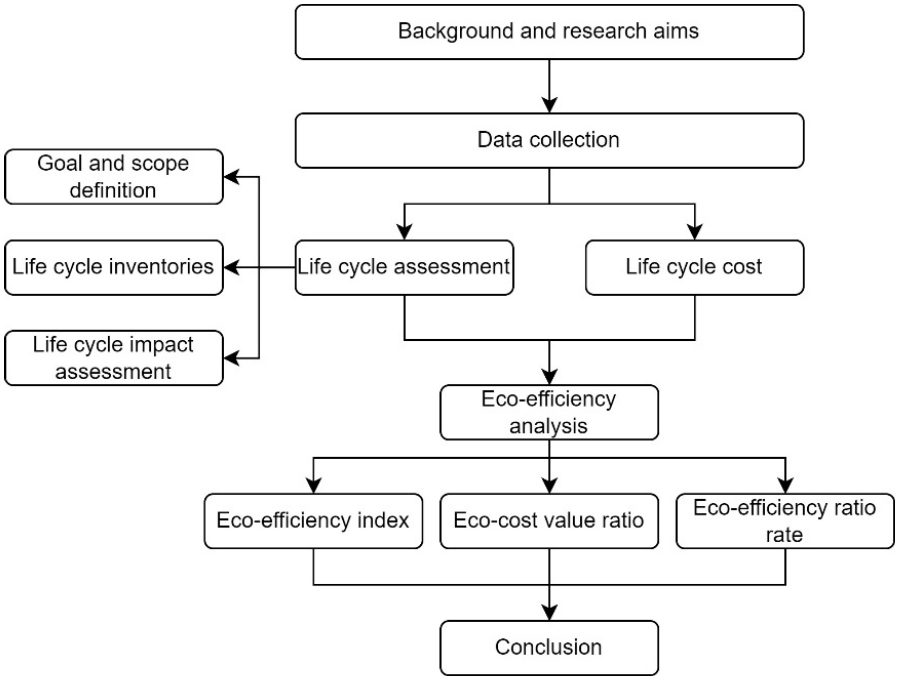

Fig. 1: Methodological framework of the study

cycle impact assessment, and interpretation. LCC calculations were conducted by determining the raw materials, production, transportation, and waste-processing costs. From the LCC and LCA results, EE can be determined by calculating the EE index (EEI), eco-cost value ratio (EVR), and eco-efficiency ratio rate (EER). Several conclusions were drawn from these results. The three main hypotheses were as follows: 1) the addition of waste recycling increases the environmental impact because it adds the number of activities, 2) the waste recycling scheme also increases the cost of production and maintenance, and 3) the recycling scheme in this study has a higher EE than others because of the product produced by the system. The methodological framework of this study is illustrated in Fig. 1. This study had some limitations, including failing to consider the transportation of the waste materials to the recycling facility and the possibility of substituting fuel for cooking and frying. In the case of Sugihmanik Tofu SME, corncobs were used for cooking and rice husk for frying. In the other tofu SMEs, the type of fuel could be different depending on the abundance of resources in the area. This activity may result in different environmental and economic effects in other areas.

Study location profile

Situated within the Tanggungharjo Subdistrict of the Grobogan Regency in Central Java, Sugihmanik Village spans an expanse of 1,286,600 hectares (ha) based on 2020 statistical records. This village is home to eight hamlets with a predominant portion of its population engaged in tofu production. Sugihmanik Village accommodates over 30 SMEs that continue to employ traditional methods for tofu production. On average, each SME yields 150 kg of soybean and consumes 3,000–5,000 L of additional water daily (Hartini *et al*., 2023). The substantial volume of tofu production in Sugihmanik Village is directly linked to considerable waste output. Hartini *et al.* (2021) conducted examinations on tofu wastewater and river water and found that tofu wastewater had BOD ranging 3,667 – 4,933 mg/L, COD ranging 7,668 – 9,736 mg/L, and total suspended solid (TSS) content of 701 – 1,189 mg/L. By contrast, the river water in Sugihmanik Village had a BOD of 367 mg/L and a COD of 738 mg/L. These measurements exceed the wastewater quality standards stipulated by Central Java Provincial Regulation No. 5 of 2012. The management of waste generated by tofu production remains a challenge, particularly the proper disposal of wastewater that poses a threat to the cleanliness of river ecosystems (Mihai *et al.,* 2021). The Ministry of Environment and Forestry of Indonesia highlights that wastewater from tofu production comprises dissolved or suspended solids that can undergo chemical, physical, and biological transformation. These wastewater components contribute to the discoloration and turbidity of river water, causing unpleasant odors and deterioration of river water quality (Hartini *et al.,* 2021). As indicated by these circumstances, the SMEs engaged in tofu production within Sugihmanik Village have not yet fully adopted effective waste management strategies. The SMEs in Sugihmanik Village are still representative of the industries characterized by suboptimal energy efficiency and elevated environmental pollution levels (Kurniawati *et al.,* 2019). From January to September 2021, the prevailing wind direction was from the south. According to data from the Semarang Climatology Station, the wind heading towards Sugihmanik village had speeds ranging from 3.00 – 6.00, accounting for 8.63% of the time, and speeds between 6.00 and 9.00, making up 2.63%. Winds exceeding 9.00 occurred 1% of the time. The highest sunlight duration in 2021 (January – September) was recorded in August, with an average of 8.95 hours per day. The average temperature in Sugihmanik village ranged from 26.71 °C to 29.00 °C, with average humidity levels between 70.6% and 91.4%. Throughout 2021, Sugihmanik has experienced rainfall ranging from 0 to 660 mm per month, which was significantly higher than the Indonesian average of 167 – 250 mm per month. The village of Sugihmanik is situated at elevations varying from 12 m to 60 m above sea level. Eko Budi Tofu SME (−7.097558, 110.616705) is one of the 30 tofu SMEs located in Sugihmanik Village (Fig. 2). This SME was established in 2015 and employs two workers responsible for processing raw soybean materials into fried tofu. Eko Budi Tofu SME typically produces tofu using soybean as the main ingredient, and the resulting tofu products are sold at Ganefo Market in Mranggen and Johar Market in Semarang City. Essentially, the tofu production in Sugihmanik Village is still carried out in a traditional manner with limited resources. Given that their production patterns can be assumed to be similar, this study focused on one SME as a representative of all tofu SMEs in Sugihmanik Village.

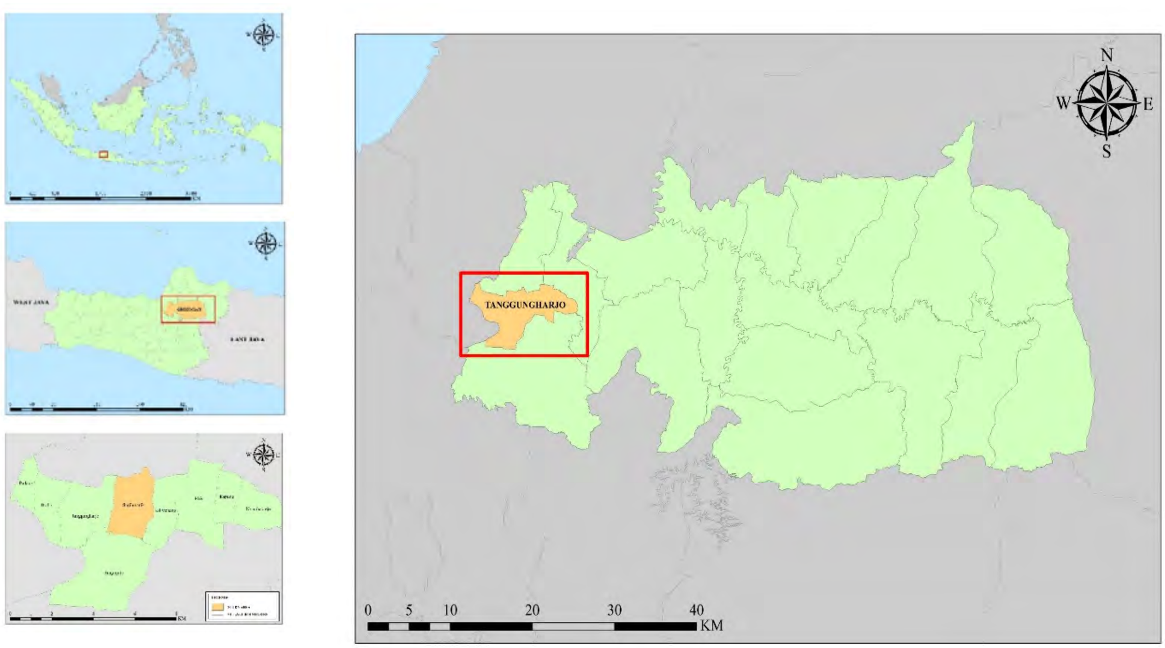

Fig. 2: Geographic location of the study area in Sugihmanik Village in Indonesia

Data collection

Interviews with workers at SMEs tofu production and individuals who could provide information regarding the processing of tofu production waste were conducted to obtain information that will be used to develop the life-cycle inventory for this study. The goal was to gather insights into the process, inputs, outputs, and associated costs that could help address this study problem.

Goal and scope definition

In the initial stage of the LCA, the study objectives and scope were determined. LCA was used to assess the life cycle of the tofu industry and its potential recycling scenario, which can be divided into four products: tofu as the main product and briquettes, swollen tempeh, and nata de soya as secondary or recycling products. This study focused on cradle-to-grave (tofu production) and cradle-to-cradle (tofu production to waste recycling) by examining the materials and energy production chain throughout all stages, from the extraction of raw materials through production, transportation, and use, until the end of the product's life cycle. The functional unit of this study was one batch production of tofu or 9 kg of fried tofu. The first assessment evaluated the existing tofu production process (cradle-to-grave), and several products were assessed as recycling systems. The goal of this step was to identify the environmental impacts and costs (eco-cost) of the tofu production and its waste recycling scenarios. The evaluated system encompassed the tofu production stages, which include soaking, mixing, cooking, filtering, clumping, molding, and frying. In LCA, inputs refer to the raw materials used during production, and outputs refer to the waste generated. Both were measured in units of mass (kg), volume (L), and electricity consumption (kWh). The goal of the second assessment was to identify the environmental impacts and eco-costs from the tofu production to the recycling of the generated waste (cradle-to-cradle). Three products were proposed as recycled and nontofu products. The first evaluated product was the conversion of wastewater to nata de soya, the second was the conversion of tofu dregs to tempeh, and the third was the use of husk charcoal as briquettes. The scope of the study and system boundaries are shown in Fig. 3.

Life cycle inventory (LCI)

In the second stage, the inputs and outputs for each scenario of tofu waste processing were identified. The information required at this stage includes energy requirements, materials used, and waste generated. Using input information from the previous stage, this process was accomplished with the SimaPro software version 9.4. LCI reveals the inputs and outputs associated with the tofu production and waste recycling scenarios as an extension of the conventional production system. The output network LCI diagram provides information about the relationships between each process that generate environmental impacts for the conventional and proposed scenarios. Table 1 lists the data inventories used in the impact assessments. The variable cost data in Table 1 were justified according to the respondents' experiences and best practices.

Life cycle impact assessment (LCIA)

In the third stage, an analysis was conducted to determine the types and magnitudes of the generated impact categories. LCIA uses the eco-cost 2023 method, which consists of four stages: characterization, normalization, weighting, and derivation of a single score. The eco-cost values were obtained from the LCIA stage and used to calculate eco-efficiency. Twelve impact categories were assessed: carbon footprint, acidification, eutrophication, photochemical ozone formation, particulate matter (PM), human toxicity (cancer and non-cancer), ecotoxicity (freshwater), metal scarcity, uranium use, land use, and baseline water stress.

LCC

LCC encompasses all the costs related to the lifecycle of a product spent by one or more stakeholders throughout the lifecycle. These types of costs include those incurred from production until the emergence of a finished product for each scenario of the tofu industry waste processing. Such as raw material, production (equipment), labor, marketing, and waste processing costs for each scenario of tofu production waste processing. Data were processed using the LCC method, which involves calculating the overall cost of tofu production for each scenario of tofu production waste processing. In this study, USD 1 was equal to IDR 15,590. LCC can be calculated using Eq. 1 (Mendoza *et al.*, 2019).

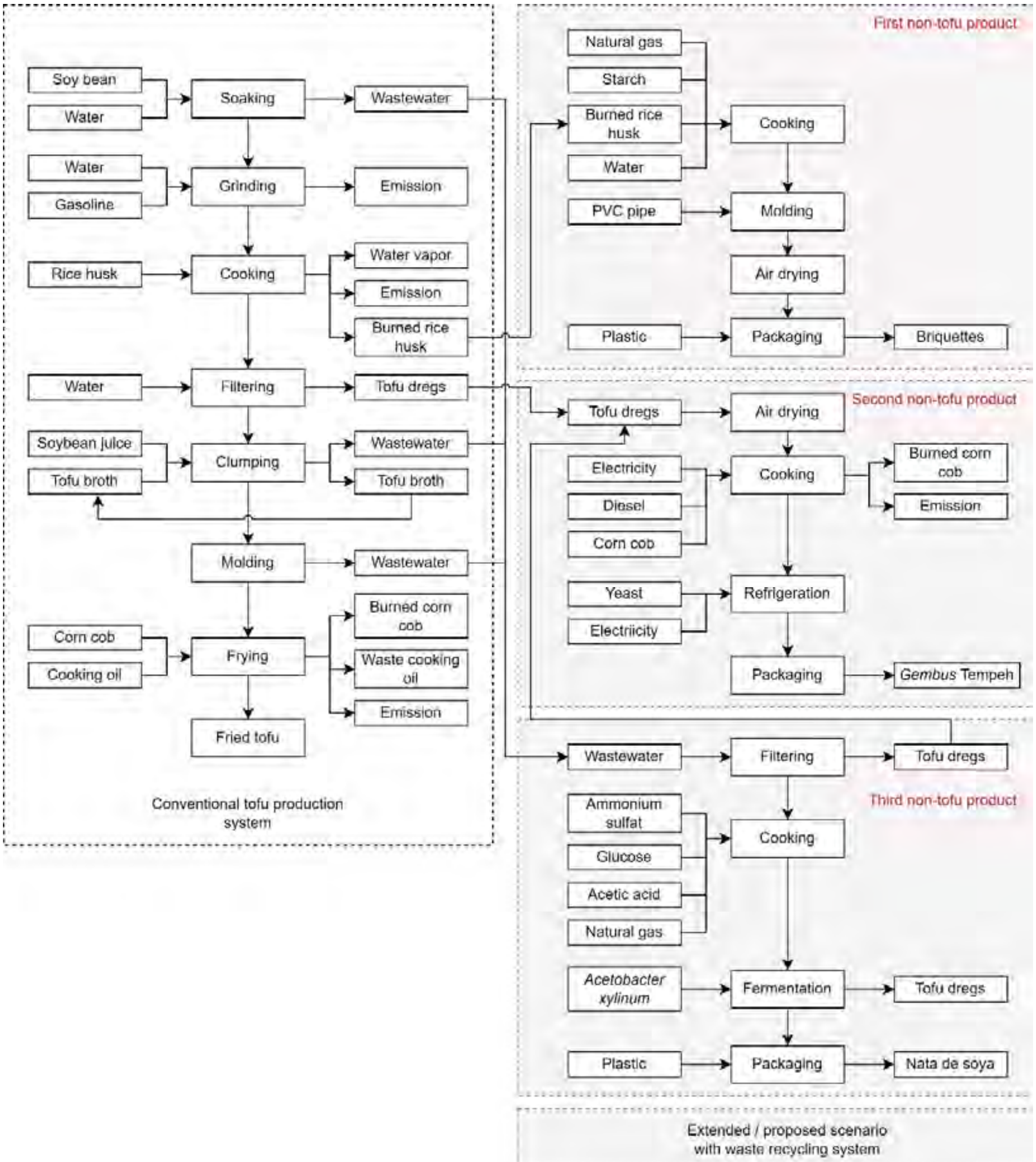

Fig. 3: System boundaries and input–output flow diagram

$$LCC = CRM + CM + CT + CWM, \quad (1)$$

where CRM is the raw material cost, CM is the product manufacturing cost, CT is the transportation cost, and CWM is the waste treatment cost. The net value calculation used for the subsequent eco-efficiency calculations employed in Eq. 2 (Hartini *et al*., 2021).

$$Net\,Value = Selling\ Price - Production\,costs \quad (2)$$

According to Hartini *et al.* (2021), the net value is the disparity between selling price and production costs. In the present study, the net value was determined via cost–benefit analysis based on the following assumptions for each scenario: 5 working hours daily, 25 days monthly, 90 L of wastewater,

Table 1: LCI and input–output amount

Process unit	Input components (unit)	Amount	Output components	Amount
			Conventional tofu production system	
Soaking	Soy bean (kg)	5	Soy bean (kg)	9
	Water (L)	12	Wastewater (L)	8
Grinding	Water (L)	14	Soy bean juice (kg)	23
	Gasoline (L)	0.13		-
	Soy bean (kg)	9		-
Cooking	Water (L)	60	Tofu porridge (kg)	79
	Rice husk (kg)	6.5	Water vapor (kg)	4
	Soy bean juice (kg)	23	Burned rice husk (kg)	1.6
Filtering	Water (kg)	30	Tofu dregs (kg)	10
	Tofu porridge (kg)	79	Soybean juice (kg)	99
Clumping	Soybean juice (kg)	99	Wastewater (L)	76
	Tofu broth (L)	23	Tofu juice (kg)	23
			Tofu broth (L)	23
Molding	Tofu juice (kg)	23	Wastewater (L)	14
			Raw tofu (kg)	9
Frying	Cooking oil (L)	0.9	Waste cooking oil (L)	0.3
	Corn cob (kg)	3.7	Burned corn cob (kg)	0.9
	Raw Tofu (kg)	9	Fried tofu (kg)	9
				Extended scenario
				Briquettes
Cooking	Water (L)	0.5	Raw material of briquettes (kg)	2.6
	Starch (kg)	0.5		
	Burned rice husk (kg)	1.6		
	Natural gas (kg)	0.1		
Drying	Raw material of briquettes (kg)	2.6	Briquettes (kg)	2.6
Packing	Briquettes (kg)	2.6	Briquettes (kg)	
	Plastics (kg)	0.0625		
				Swollen Tempeh
Drying	Tofu dregs (kg)	10	Wastewater (L)	1
			Tofu dregs (kg)	9
Cooking	Tofu dregs (kg)	9	Raw material of swollen tempeh (kg)	9
	Corn cob (kg)	2		
	Electricity (kWh)	0.03		
	Gasoline (L)	0.025		
Refrigeration	Raw material of swollen tempeh (kg)	9	Swollen tempeh (kg)	9.075
	Yeast (kg)	0.075		
	Electricity (kWh)	0.12		
Packing	Swollen tempeh (kg)	9.075	Swollen tempeh (kg)	9.32
	Plastic (kg)	0.25		
				Nata de Soya
Filtering	Wastewater (L)	90	Wastewater (L)	89
			Tofu dregs (kg)	1
Cooking	Wastewater (L)	89	Raw material of nata de soya (kg)	92.6
	Ammonium sulfate (kg)	0.45		
	Glucose (kg)	2.25		
	Acetic acid (L)	0.9		
	Natural gas (kg)	0.1		
Fermentation	Raw material of nata de soya (kg)		Nata de soya (kg)	93.5
	Acetobacter xylinum (kg)	0.9		
Packing	Nata de soya (kg)	93.5		
	Plastic	0.25		

Table 2: LCC inventory recapitulation

Component	Existing condition (USD)	Full extension (USD)	Existing + briquettes (USD)	Existing + swollen tempeh (USD)	Existing + nata de soya (USD)
Raw materials cost	4.60	21.83	4.89	5.45	20.64
Production cost	0.67	1.52	0.94	0.95	0.98
Transportation cost	0.46	1.48	0.74	0.99	0.74
Waste processing cost	15.39	-	-	-	-
Total cost	21.12	24.83	6.57	7.39	22.36

1.6 kg of solid waste (rice husk charcoal), and 10 kg of solid waste (tofu residue) per tofu production. Material costs were assessed by multiplying the material unit price by the quantity used, and material quantity was determined through direct observation and interviews. Equipment costs, which are incurred to support production, were calculated by multiplying the equipment cost by the number of units, and labor costs (i.e., operator count and batch wage cost). Overhead costs, including electricity and equipment depreciation, are considered additional costs. Marketing costs, including vehicle, fuel, and vehicle depreciation, account for the production cost. Table 2 presents the recapitulation of the LCC inventory.

EE

The EVR is used to determine the ratio of eco-cost to the net value generated by a product. Its output provides the ratio between the eco-cost and net value. This ratio helps to assess the environmental cost in relation to the economic value of a product or process, offering insights into the sustainability and efficiency of the system being analyzed. The final stage of data processing in this study involved calculating the output results from the LCA and LCC methods for tofu production waste processing scenarios. The EEI, EVR, and EER were calculated using Eqs. 3 to 5 (Hartini *et al*., 2021).

$$EEI = (Net\,Value)/(Eco\,Cost) \quad (3)$$

$$EVR = (Eco\,Cost)/(Net\,Value) \quad (4)$$

$$EER = (1 - EVR) \times 100\% \quad (5)$$

RESULTS AND DISCUSSION

Interpretation of LCIA

Tofu production can generate waste that may contribute to environmental degradation. As it is found in this study, 9 kg of tofu can generate 10 kg of tofu dregs, 98 liter of wastewater, and 1.6 kg of burned rice husk, 0.3 L of waste cooking oil, and 0.9 kg of burned corn cob. In this study, only three wastes were recycled, which were determined based on the possibility of a recycling system that can be developed in the area. Almost all tofu dregs, wastewater, and burned rice husks can be recycled without further waste. During tofu waste production, several direct emissions from grinding, cooking, and frying were recorded (Fig. 3). This study identified the significant environmental impacts in various categories. For instance, the carbon footprint category showed the highest impact on the production of tofu and conversion of wastewater to nata de soya. This process resulted in an emission of 3.955 kg CO_2eq, with the individual tofu production and waste processing phases contributing 2.03 and 2.434 kg CO_2eq, respectively. The acidification category had the most significant impact on the use of wastewater in production and conversion processes. The highest acidification impact was observed at 0.43 moles hydrogen ion equivalent (mol H^+eq), with distinct contributions from the tofu production and waste processing stages. Eutrophication analysis underscored that wastewater processing from tofu production to nata de soya conversion had the greatest impact of 4.6 kg of phosphate equivalent (PO_4eq). By contrast, the processing of rice-husk charcoal waste into briquettes demonstrated the lowest impact at 0.06 kg PO_4eq. The photochemical ozone formation category had the largest impact on tofu production to wastewater conversion into nata de soya, amounting to 0.406 kg of nonmethane volatile organic compound equivalents (NMVOC-eq). Similarly, particulate matter emissions showed the highest impact on tofu production to wastewater conversion to nata de soya (0.256 kg $PM_{2.5}$). The

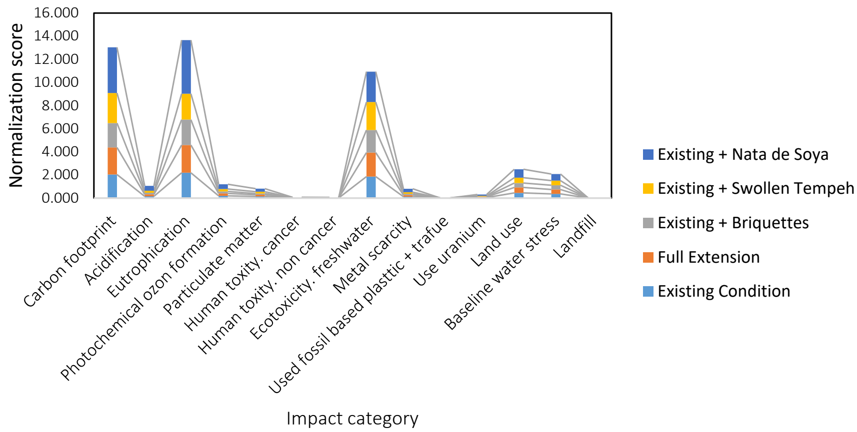

Fig. 4. Impact assessment results of existing condition vs. extended scenario

human toxicity category had the greatest impact on processing tofu waste for wastewater conversion (0.0159 comparative toxic units for humans (CTUh) for cancer and 0.016 CTUh for noncancer). In the freshwater ecotoxicity category, significant impacts were observed on tofu production waste to wastewater conversion to nata de soya (2.618 CTU-eq). Conversely, the lowest freshwater ecotoxicity impact was observed in the conversion of rice husk charcoal waste to briquettes (0.53 CTU-eq). The categories of metal scarcity, uranium use, land use, and baseline water stress were also explored for their respective environmental impacts with varying levels of significance (Fig. 4).

LCC assessment results

The calculations yielded the following LCC figures: USD 21.12 for the cradle-to-grave tofu production and USD 24.83 for the processes from tofu production to waste recycling (wastewater and solid waste). The highest LCC was attributed to the cradle-to-cradle process or waste recycling scenario. The high cost of waste recycling was primarily attributed to cumulative expenses from the derivation of the three nontofu products. The second highest cost was associated with waste processing in the production of nata de soya, owing to the significant wastewater portion in the tofu production (60%) and the use of costly starter bacteria, *Acetobacter xylinum*, during fermentation. The high eco-cost for the recycling system indicates a higher production cost for developing the recycling scenario. However, the environmental cost is even higher when no recycling system is applied, which is not good and efficient for the environment. This assertion was supported by Mendoza *et al.* (2019), who emphasized that raw materials constitute over 85% of the total product costs, followed by transportation and waste management at 7% and 3%. Manufacturing accounted for only 2% of the overall cost. After the LCC was obtained, the subsequent step involves calculating the net value for each process, which is pivotal for deriving the EEI. Net value calculations were USD 1.33 for cradle-to-grave and USD 38.99 for cradle-to-cradle tofu production and waste recycling. Table 3 presents the comparison results of eco-costs for the scenarios evaluated in this study.

EEI results

The EEI values categorized the products as follows. The processes of tofu production (cradle-to-grave) and the tofu production to solid waste processing (rice husk charcoal to briquette scenario) are deemed affordable and unsustainable. Conversely, the processes from tofu production to waste recycling, such as the conversion of wastewater to nata de soya, solid waste (tofu residue) to swollen tempeh, and solid waste (rice husk charcoal) to briquettes, fall under the category of affordable and sustainable. “Affordable” signifies economic efficiency and profitability, and “sustainable” implies that the production process has minimal environmental impact. The tofu production process lacks sustainability owing to factors such as the direct discharge of wastewater into rivers, accumulation of rice husk and tofu residue waste, electricity consumption for water pumps, and

Table 3: Eco-cost results comparison between scenarios (in USD)

No.	Impact Category	Existing condition	Full extension	Existing + briquettes	Existing + swollen tempeh	Existing + nata de soya
1	Carbon footprint	1.910	2.204	1.980	2.453	3.723
2	Acidification	0.129	0.160	0.133	0.164	0.405
3	Eutrophication	2.057	2.253	2.071	2.109	4.363
4	Photochemical ozone formation	0.169	0.198	0.160	0.206	0.382
5	Particulate matter	0.122	0.139	0.105	0.148	0.241
6	Human toxicity. cancer	0.008	0.009	0.009	0.010	0.015
7	Human toxicity. non cancer	0.007	0.008	0.007	0.009	0.015
8	Ecotoxicity. freshwater	1.739	1.952	1.838	2.286	2.464
9	Metal scarcity	0.107	0.126	0.113	0.127	0.274
10	Used fossil based plastic + trafue	0.000	0.000	0.000	0.000	0.000
11	Use uranium	0.039	0.047	0.038	0.050	0.107
12	Land use	0.411	0.446	0.359	0.433	0.690
13	Baseline water stress	0.331	0.360	0.349	0.368	0.543
14	Landfill	0.000	0.000	0.000	0.000	0.000
Total		7.029	7.902	7.162	8.362	13.222

resulting emissions. Inadequate waste disposal can result in harmful environmental impacts (Hartini *et al*. 2023). The evaluation demonstrated that the primary environmental impacts of the tofu production include carbon footprint, eutrophication, and ecotoxicity (freshwater) (Hartini *et al*., 2021). Similarly, the processes from tofu production to solid waste treatment (rice husk charcoal to briquette scenario) are unsustainable owing to several factors. First, the significant environmental impact of the initial tofu production influences the overall waste treatment. This assertion was further substantiated by the calculated EEI value for solid waste treatment when separated from the tofu production, which falls within affordable and sustainable categories. Second, the environmental expenses surpass the product profits. The limited net value stems from the fact that a single tofu production cycle produces 1.6 kg of rice husk charcoal waste out of 101 kg of waste. The profit or net value from converting solid waste (rice-husk charcoal) to briquettes (rice-husk charcoal to briquette scenario) does not adequately cover the requisite environmental costs. This finding was aligned with the study of Zuraida *et al.* (2022), who asserted that the environmental impact of a production process leads to high eco-costs borne by the company. Beyond potential unsustainability stemming from environmental impacts, production costs also shape a product's sustainability. High production costs are correlated with reduced process efficiency and potential for an unsustainable product.

EVR results

Table 4 indicates that the tofu production exhibited a relatively high EVR of 5.3. Its ecological dimension amounted to USD 7.03, and its economic dimension amounted to USD 1.33. The elevated EVR values for the processes from tofu production to converting rice husk charcoal to briquette stem from the eco-costs being two to five times higher than the net value, indicating inefficient production practices that result in negative environmental consequences. In general, a low EVR indicates an improved feasibility and suitability for product manufacturing. By contrast, the extension scenarios in this study displayed EVR values below 1, indicating their suitability for production. This result concurred with the study of Vogtlander *et al.* (2017), who stated that a small EVR signifies good suitability and feasibility for product manufacturing because enhanced production efficiency leads to diminished adverse environmental impacts.

EER results

Table 4 shows that the EER for the tofu production exceeded 100%, suggesting that the process falls short of satisfying the ecological and economic aspects. This finding aligned with the study of Hartini *et al.* (2021), who asserted that an EER value surpassing 100% indicates that the net value is inferior to environmental impact costs (eco-costs). To

Table 4: Eco-efficiency comparison

Assessment	Existing condition	Full extension	Existing + Briquettes	Existing + Swollen Tempeh	Existing + Nata de Soya
Eco cost (USD)	21.12	24.83	22.36	9.29	6.57
Net value (USD)	1.33	38.99	28.95	9.29	3.37
Eco-efficiency index	0.18	5	2.1	1.1	0.4
Eco-cost value ratio	5.3	0.2	0.4	0.9	2.1.
Eco-efficiency ratio rate	-430%	80%	60%	10%	-110%

enhance the EER of a product, either the net value must increase or the cost factors encompassing production and environmental costs (eco-costs) must decrease. Conversely, a decline in EER was observed for the processes from tofu production to proper waste processing for solids and wastewater. Initially at −430%, this shift in EER signifies that comprehensive waste recycling contributes to economic and environmental efficiency enhancement.

Overall results and significant findings

This study focused on the transformation of tofu production waste or recycling of tofu waste into several products or resources such as nata de soya, swollen tempeh, and briquettes. According to literature, GHG emissions from tofu production vary significantly. This study estimated 0.4 kg CO_2e which is lower than those from other analyses at approximately 1.0 kg CO_2e (Mejia *et al*., 2017) to 1.9 kg CO_2e (Blonk *et al*., 2008) per kg of tofu production. The differences in the estimation of GHG emissions are attributed to several factors, including the type of allocation method used (economic vs. attributional); inclusion of additional elements such as transportation to retailers, cooking, and waste disposal; differences in technology; and climatic conditions (Mejia *et al*., 2017). The forecasting result has a different pattern from the findings of Rosyidah *et al.* (2020), who found a high impact from human health, ecosystem quality, and resources. This difference in estimation is attributed to several reasons, including the use of different impact categories and characterization methods, and different assumptions on the material used for cooking and frying.

The high value of the eutrophication category is responsible for the excessive richness of nutrients in the water body, which leads to dense growth of plant life and aquatic animals due to a lack of oxygen. Tofu production, which produces an exceedingly high amount of wastewater, can contribute to high nutrients in the water body (Saba *et al.*, 2023). Regarding the carbon footprint, the GHG emissions from tofu production are high, indicating that tofu production has a high carbon footprint accumulating from its various processes such as frying and cooking and other activities that contribute to GHG emissions (Budihardjo *et al*., 2023). Freshwater ecotoxicity refers to the potential for biological, chemical, and physical alterations in freshwater ecosystems. Tofu production has significant implications for freshwater ecosystems (Mendoza *et al*., 2019). This study found that waste can be used to create a circular economy and sustainability in food processing by building a beneficial circular economy model. These alternative waste recycling techniques are simple, affordable, and available locally. The establishment of business-centered activities that focus on handling waste products could significantly boost the local economy. These businesses can be operated individually or by local communities to obtain value from the waste materials. An estimated net profit of USD 38.99 per tofu production can be scaled up to over USD 962.16 per day on the daily capacity of each tofu SMEs. This study highlighted the principles of a circular economy, which converts waste output into valuable input for a new process. This approach can generate economic value and promote sustainable waste reduction. Expanding the recycling model to include additional SMEs may enhance the environmental and economic benefits on a large scale (Zhang *et al*., 2020). In addition, LCA could be broadened to include the entire life cycle, encompassing a comprehensive range of inputs such as land use and environmental consequences. Directly comparing tofu with other foods, especially those that tofu might partially replace, would enhance the usefulness of this study. Expanding the analysis to include the health impacts of tofu consumption would also be beneficial. In summary, this study utilized a thorough, up-to-date, validated, original, and distinctive dataset obtained from a leading tofu producer in the United States. LCA from the point of cultivation to factory exit demonstrated that tofu, a protein-rich plant-based food, is associated with relatively low GHG emissions (Mejia *et al*., 2017).

CONCLUSION

This study provides an alternative for processing tofu production waste, which has been a problem for the community around Sugihmanik Village. The suggested waste processing alternatives are easy to understand, simple to execute, use materials readily available to the community, and most importantly, are relatively affordable. Their availability opens up new business ideas for the people around Sugihmanik Village by utilizing tofu production waste, which was previously discarded directly into the environment (waste), as the main material (resource). The establishment of new businesses related to tofu production waste processing will undoubtedly boost the local economy by adding value to this previously considered waste. The results of this study also illustrate that tofu production waste processing can yield higher profits than simply disposing of tofu production waste into the environment without proper processing. The net profit or earnings generated from the processing of tofu waste into three products—nata de soya, swollen tempeh, and briquettes—is USD 38.99 in one tofu production process. With a daily tofu production capacity of 30 times, this profit can reach over USD 962.16 per day from tofu production waste processing efforts. This study applies the concept of a circular economy by utilizing the outputs from tofu production process, such as liquid and solid waste, which were previously considered waste, as inputs (resources) for the subsequent process. The process involves treating waste using three waste recycling paths, resulting in the production of nata de soya, swollen tempeh, and briquettes. These products are then ready to be distributed to the community with added value from each waste product. This principle allows the reuse of waste from a process, creating a sustainable loop in resource utilization. LCA calculations revealed eutrophication, carbon footprint, and ecotoxicity (freshwater) to be the three largest impact categories for each process. According to the results of the eco-cost 2023 analysis, the eco-cost values for tofu production (cradle-to-grave) and extension scenarios were USD 7.03 and USD 7.90. LCC calculation showed that the largest LCC value originated from the recycling scheme, amounting to USD 24.83. The net value or profit generated from tofu production for overall waste processing was USD 38.99. The high net value or profit obtained from the cradle-to-cradle process reinforces that proper waste management during tofu production can yield substantial profits while reducing the negative environmental impacts of tofu production waste. The calculated eco-efficiency values from the conventional tofu production and the extended recycling scheme indicated a significant positive increase in EEI from 0.18 to 5. Waste processing scenarios involving nata de soya, swollen tempeh, and briquettes fell into the affordable and sustainable category. This finding suggested that the waste processing products from this study are suitable for recommendation because of their ability to enhance economic value and reduce environmental impact. Considering the simple waste-processing process, easily accessible materials, and affordable production costs, this scheme could potentially open new business opportunities for the community. Future studies should consider the impact assessment and environmental costs of processing tofu production waste in various scenarios and compare it with alternative methods, such as converting liquid waste into soy sauce and liquid fertilizer and processing solid waste (tofu dregs) into flour and crackers. Owing to its environmental and economic benefits, this recycling system should be endorsed for application to all SMEs to help determine which tofu production waste processing method has the lowest environmental impact and highest economic value enhancement.

AUTHOR CONTRIBUTIONS

S. Hartini performed the experimental design, analyzed and interpreted the data, prepared the manuscript text and edition. A.N. Fatliana performed the literature review, experimental works, compiled the data, and data analysis. N.U. Handayani helped in the data collection, literature review and manuscript preparation. Wicaksono P.A. contributed to the data analysis, prepared the manuscript text, and interpreted the results. B.S. Ramadan drafted the manuscript, reviewed the final version of the manuscript, and developed the experimental design.

T. Matsumoto reviewed the results and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°C	Degree of Celsius
BOD	Biological oxygen demand
CH_4	Methane
COD	Chemical oxygen demand
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CTUh	Comparative toxic unit for human
EE	Eco-efficiency
EEI	Eco-efficiency index
EER	Eco-efficiency ratio rate
Eq.	Equation
EVR	Eco-cost value ratio
Fig.	Figure
GHG	Greenhouse gas
g	Gram
GWP	Global warming potential
ha	Hectare
kg	Kilogram
$kg\ CO_2eq$	Kilogram of carbon dioxide equivalent
kWh	KiloWatt hours
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventories
LCIA	Life cycle impact assessment
mm	Milimeter
mg/L	Miligram per liter
MJ/kg	Mega Joule per kilogram
$Mol\ H^+eq$	Moles hydrogen ion equivalent
NMVOC-eq	Non-methane volatile organic compound equivalents
NO_x	Nitrogen oxide
$(NO_x)eq$	Nitrogen oxide equivalent
PM	Particulate matter
PO_4eq	Phospate equivalent
SMEs	Small- and medium-sized enterprises
TSS	Total suspended solids
USD	United States Dollar

REFERENCES

Ajijah, N.; Tjandra, B.C.; Hamidah, U.; Sintawardani, N., (2020). Utilization of tofu wastewater as a cultivation medium for Chlorella vulgaris and Arthrospira platensis. IOP Conference Series: Earth Environ. Sci., 483(1): 012027 **(9 pages)**.

Al-Shami, S.; Rashid, N., (2022). A holistic model of dynamic capabilities and environmental management systems for eco-product innovation and sustainability in automobile firms. J. Bus. Ind. Mark., 37(2): 402-416 **(15 pages).**

Bahri, S.; Hadati, K.S.; Satrimafitrah, P., (2021). Production of protein hydrolysate from tofu dregs using the crude extract of bromelain from pineapple core (Ananas comosus l). Conference Series: J. Phys., 1763(1): 012008 **(10 pages)**.

Blonk, H.; Kool, A., Luske, B., de Waart, S. (2008). Environmental effects of protein-rich food products in The Netherlands: consequences of animal protein substitutes.

Budihardjo, M.A.; Ardiansyah, S.Y.; Ramadan, B.S., (2022). Community-driven material recovery facility (CdMRF) for sustainable economic incentives of waste management: Evidence from Semarang City, Indonesia. Habitat Int., 119: 102488 **(10 pages)**.

Budihardjo, M.A.; Priyambada, I.B.; Chegenizadeh, A.; Al Qadar, S.; Puspita, A.S., (2023). Environmental impact technology for life cycle assessment in municipal solid waste management. Global J. Environ. Sci. Manage., 9(SI): 145-172 **(28 pages)**.

Colimoro, M.; Ripa, M.; Santagata, R.; Ulgiati, S., (2023). Environmental impacts and benefits of tofu production from organic and conventional soybean cropping: improvement potential from renewable energy use and circular economy patterns. Environments, 10(5): 73 **(30 pages)**.

Dai, Y.; Wang, Z.; Li, J.; Xu, Z.; Qian, C.; Xia, X.; Liu, Y.; Feng, Y., (2023). Tofu by-product soy whey substitutes urea: Reduced ammonia volatilization, enhanced soil fertility and improved fruit quality in cherry tomato production. Environ. Res., 226: 115662 **(11 pages)**.

Dewilda, Y.; Fauzi, M.; Aziz, R.; Utami, F.D., (2023). Analysis of food industry waste management based-on the food recovery hierarchy and 3R concept-A case study in Padang City, West Sumatra, Indonesia. J. Ecol. Eng., 24(7): 198–208 **(11 pages)**.

Esteban, J.; Ladero, M., (2018). Food waste as a source of value-added chemicals and materials: a biorefinery perspective. Int. J. Food Sci. Technol., 53(5): 1095-1108 **(14 pages)**.

Gultom, E.; Hestina, H.; Florentina, N.; Aritonang, B., (2021). Paper making and characterization from waste coconut and tofu dregs. J. Pendidikan Kimia (JPKIM), 13(2): 159-171 **(13 pages)**.

Hartini, S.; Azzahra, F.; Purwaningsih, R.; Ramadan, B.S.; Sari, D.P., (2021). Framework for Increasing Eco-efficiency in the Tofu Production Process: Circular Economy Approach. Prod. Eng. Arch., 29 (December 2023): 452–460 **(9 pages)**.

Hartini, S.; Ramadan, B.S.; Purwaningsih, R.; Sumiyati, S.; Kesuma, M.A.A., (2021). Environmental impact assessment of tofu production process: case study in SME Sugihmanik, Grobogan. IOP Conference Series: Earth Environ. Sci., 894: 012004 **(9 pages)**.

Hulu, A., (2023). Study of policy innovation strategy to accelerate achievement of Indonesian soybean self-sufficiency in 2035. Matra Pembaruan, 7(1): 13–23 **(11 pages)**.

Jain, A.; Sarsaiya, S.; Awasthi, M.K.; Singh, R.: Rajput, R.; Mishra, U.C.; Chen, J.; Shi, J., (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks. Fuel, 307: 121859 **(13 pages)**.

Karlović, A.; Jurić, A.; Ćorić, N.; Habschied, K.; Krstanović, V.; Mastanjević, K., (2020). By-products in the malting and brewing industries—re-usage possibilities. Fermentation, 6(3): 82 **(17 pages)**.

Kurniawan, T.A.; Meidiana, C.; Othman, M.H.D.; Goh, H.H.; Chew, K.W., (2023). Strengthening waste recycling industry in Malang (Indonesia): Lessons from waste management in the era of Industry 4.0. J. Cleaner Prod., 382: 135296 **(14 pages)**.

Kurniawati, S.D.; Supartono, W.; Suyantohadi, A., (2019). Life cycle assessment on a small scale tofu industry in Baturetno village, Bantu district Yogyakarta. IOP Conference Series: Earth Environ. Sci., 365: 012066 **(6 pages)**.

Masayu, R.; Masruri, A.; Putra, R.A.; Mayanita, Ananda, Cindy. (2020). Analysis of environmental impact with the life cycle assessment (LCA) method on tofu production. Int. J. Sci. Technol. Manage., 1(4): 428-435 **(7 pages)**.

Mejia, A.; Harwatt, H.; Siegl, K.J.; Sranacharoenpong, K.; Soret, S.; Sabate, J., (2017). Greenhouse gas emissions generated by tofu production: A case study. J. Hunger Environ. Nutr., 13(45): 1-12 **(12 pages)**.

Mendoza, J.M.F.; D'Aponte, F.; Gualtieri, D.; Azapagic, A., (2019) Disposable baby diapers: Life cycle costs, eco-efficiency and circular economy. J. Cleaner Prod., 211: 455-467 **(13 pages)**.

Mihai, F.C.; Gündoğdu, S.; Markley, L.A.; Olivelli, A.; Khan, F.R.; Gwinnett, C.; Gutberlet, J.; Reyna-bensusan, N.; Llanquileo-Melgarejo, P.; Meidiana, C.; Elagroudy, S.; Ishchenko, V.; Penney, S.; Lenkiewicz, Z.; Molinos-Senante, M., (2021). Plastic pollution, waste management issues, and circular economy opportunities in rural communities. Sustainability, 14(1): 20 **(48 pages)**.

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages)**.

Mulyasari; Subaryono; Yosmaniar, (2022). Utilization of tofu waste from Indonesian small scale industry as fish feed through a fermentation process. IOP Conference Series: Earth Environ. Sci., 978: 012042 **(9 pages)**.

Nugroho, G.S.F.; Sulistyaningrum, R.; Melania, R.P.; Handayani, W., (2019). Environmental analysis of tofu production in the context of cleaner production: case study of tofu household industries in salatiga, Indonesia. J. Environ. Sci. Sustain. Dev., 2(2): 127-138 **(12 pages)**.

Pérez-Marroquín, X.A.; Estrada-Fernández, A.G.; García-Ceja, A.; Aguirre-Álvarez, G.; León-López, A., (2023). Agro-food waste as an ingredient in functional beverage processing: Sources, functionality, market and regulation. Foods, 12(8): 1583 **(18 pages)**.

Plamada, D.; Teleky, B.E.; Nemes, S.A.; Mitrea, L.; Szabo, K.; Călinoiu, L. F.; Pascuta, M.S.; Varvara, R.A.; Ciont, C.; Martău, G.A.; Simon, E.; Barta, G.; Dulf, F.V.; Vodnar, D.C.; Nitescu, M., (2023). Plant-based dairy alternatives—A future direction to the milky way. Foods, 12(9): 1883 **(33 pages)**.

Pushparaj, K.; Liu, W.C.; Meyyazhagan, A.; Orlacchio, A.; Pappusamy, M.; Vadivalagan, C.; Robert, A.A.; Arumugam, V.A.; Kamyab, H.; Klemeš, J.J.; Khademi, T.; Mesbah, M.; Chelliapan, S.; Balasubramanian, B., (2022). Nano-from nature to nurture: A comprehensive review on facets, trends, perspectives and sustainability of nanotechnology in the food sector. Energy, 240: 122732 **(17 pages)**.

Qiu, Y., Li, C., Dong, H., Yuan, H., Ye, S., Huang, X., Zhang, X.; Wang, Q., (2022). Analysis of key fungi and their effect on the edible quality of HongJun tofu, a Chinese fermented okara food. LWT, 172: 114151 **(11 pages)**.

Ropiudin, R.; Syska, K., (2023). Green manufacturing for rural tofu SMEs to increase global competitiveness: Case study in tofu industry center, Banyumas Regency, Central Java. J. Agric. Biosyst. Eng., 2(1): 168-179 **(12 pages)**.

Saba, B.; Bharathidasan, A.K.; Ezeji, T.C.; Cornish, K., (2023). Characterization and potential valorization of industrial food processing wastes. Sci. Tot. Environ., 868: 161550 **(15 pages)**.

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Sari, I.P.; Kurniawan, W.; Sia, F.L., (2021). Environmental impact of tofu production in West Jakarta using a life cycle assessment approach. IOP Conference Series: Earth Environ. Sci., 896: 012050 **(6 pages)**.

Smith, M.; Lal, P., (2022) Environmental and economic assessment of hard apple cider using an integrated LCA-LCC approach. Sust. Prod. Consum., 32: 282–295 **(14 pages).**

Syarifuddin; Anshar, K.; Subhan; Mulyawan, R., (2021). Feasibility study of potential utilization of tofu industry waste into cat fish feed. J. Sainsmat., 10(2): 82-89 **(8 pages)**.

Vogtlander, J.G.; Scheepens, A.E.; Bocken, N.M.; Peck, D., (2017). Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing. J. Remanufacturing, 7: 1-17 **(17 pages)**.

Xu, Q.; Wu, J.; Zou, L.; Ouyang, J.; Zheng, Z., (2022). Development of a process for the enhanced enzymatic digestibility of solid waste from tofu to yield fermentable biosugars. Biocatal. Biotransform., 40(1): 64-74 **(11 pages)**.

Zhang, R.; Ma, X.; Shen, X.; Zhai, Y.; Zhang, T.; Ji, C.; Hong, J., (2020). PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles. J. Environ. Manage., 260: 110062 **(11 pages)**.

Zheng, L.; Regnstein, J.M.; Teng, F.; Li, Y., (2020). Tofu products: A review of their raw materials, processing conditions, and packaging. Compr. Rev. Food Sci. Food Saf., 19(6): 3683-3714 **(32 pages)**.

Zunidra, Z.; Sondang, S.; Supriatna, S., (2022). Treatment of tofu liquid waste using anaerobic-aerobic biofilm aeration system to reduce pollution. Environ. Health Eng. Manage. J., 9(4): 391-397 **(7 pages)**.

Zuraida, S.; Armijaya, H.; Margono, R.B.; Harmaji, A.; Dewancker, B.J., (2021). A calculation approach of embodied energy, carbon emission and eco-costs on waste recycled composite materials. J. Appl. Sci. Eng., 25(1), 109-118 **(10 pages)**.

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ORIGINAL RESEARCH PAPER

Fermented palm kernel waste with different sugars as substrate for black soldier fly larvae

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ABSTRACT

BACKGROUND AND OBJECTIVES: The palm industry generates several waste products. Some of this waste, such as palm kernel meal, has not been fully optimized for processing. Therefore, this study sought to determine whether fermented palm kernel meal with various types of sugar (fructose, glucose, maltose, and sucrose) added could be utilized as a substrate for black soldier fly larvae.

METHODS: This study investigated the use of fermented palm kernel meal with various types of sugar added at a proportion of five per cent as a substrate for black soldier fly larvae. Fermented palm kernel meal without added sugar was used as a control substrate. Seven-day-old larvae were fed fermented palm kernel meal as an experimental substrate for 22 days and harvested on the final day, when their weight and length were measured and they were processed into meal and oil to evaluate their nutritional composition.

FINDINGS: The addition of sugars to fermented palm kernel meal made no significant difference to the final weight or crude fat value of the larvae, but improved crude protein. The addition of glucose significantly increased the length of the larvae and increased their lauric acid value. However, glucose-added fermented palm kernel meal significantly reduced the relative percentage of total unsaturated fatty acids and the quantities of linolelaidic, α-linolenic, and nervonic acid compared to the larvae fed on substrates with other added sugars. Meanwhile, fructose-added substrate resulted in significantly higher crude protein and moisture values, but significantly lower ash and carbohydrate values than those of other groups. Sucrose-added substrate resulted in a considerable improvement in ash content; magnesium; the relative percentage of total unsaturated fatty acids; arachidic, erucic, and docosadienoic acid; phosphorus; sodium; and iron values in the larvae. The larvae grown in the substrate with added maltose had a significantly higher accumulation of phosphorus, sodium, and iron, but showed significantly lower palmitoleic acid than other larvae groups. Calcium and potassium were accumulated better in the larvae grown on fermented palm kernel meal with added either glucose, maltose, or sucrose than other substrates.

CONCLUSION: of the various waste products generated by the palm industry, some, including palm kernel meal, have not yet been entirely processed. This study's findings offer insights into managing the fermented palm kernel meal, which can be converted into valuable biomass with black soldier fly larvae, making the waste more sustainable and rich in nutrients. The addition of various sugars to fermented palm kernel meal improved the growth and nutritional value of the black soldier fly larvae. These results may help in building a process for the effective treatment of palm kernel meal for black soldier fly larvae production, which could further develop the feed industry and manage palm industry waste effectively by generating high protein meal as a step in creating a circular bioeconomy.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
78	3	5

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INTRODUCTION

Globally, the rate of organic waste production is increasing rapidly (Mohadesi *et al.,* 2023). Over 600 million tons of organic waste were generated annually in the early years of this century, and that number is projected to approach one billion tons by 2025 (Angulo-Mosquera *et al*., 2021; Cudjoe *et al*., 2021; Liu *et al*., 2018; Widyarsana *et al*., 2021). Organic waste, such as palm kernel meal (PKM), a byproduct of oil extraction from palm fruits, significantly contributes to Indonesia's agricultural waste stream (Hambali and Rivai, 2017). The oil palm, *Elaeis guineensis*, is extensively grown in Indonesia, where it was originally introduced in 1911. According to statistics obtained from the Directorate General of Estate Crops, Ministry of Agriculture of the Republic of Indonesia, oil palm plantations in 1970 were exclusively managed by state-owned and commercial businesses. However, in 1979, small-scale farm plantations were also in operation. The total area of oil palm plantations increased from 133,298 in 1970 to 11.3 million in 2015. Indonesia's oil palm plantations are widely scattered over 22 provinces, spanning the country from west to east, as the country's favourable climatic and soil conditions permit. In 2015, Indonesia generated 37.5 million metric tonnes (MMt) of palm oil, including 31.3 MMt of crude palm oil and 6.2 MMt of palm kernel oil, from an oil palm plantation area of 11.3 MMt (Dahniar and Rusniati, 2019; Effendi *et al*., 2022; Sharma *et al*., 2005). The oil palm plantations in Indonesia are concentrated in the provinces of Sumatra and Kalimantan. These provinces collectively own the biggest oil palm acreage in the country (Austin *et al*., 2017; Dharmawan *et al*., 2020). Production projections for 2030 indicated that 54 metric tonnes (Mt) of empty fruit bunches, 31 Mt of mesocarp fruit fibres, 15 Mt of palm kernel shells, 130 Mt of palm oil mill effluent, 115 Mt of oil palm fronds, and 59.7 Mt of oil palm trunks will be produced (Hambali and Rivai, 2017). As the activity of the palm oil industry rapidly increases, its organic waste, including palm oil mill effluent, palm oil decanter, and palm kernel meal, may result in environmental harm. Therefore, organic waste should be handled using biological methods that are environmentally friendly (Samimi, 2024). Past studies have revealed that one alternative approach to managing industrial organic waste through biological methods involves using insects to convert organic waste into valuable nutrient biomass. The preferred insect is the black soldier fly (*Hermetia illucens* Linnaeus (L.); Diptera: Stratiomyidae), whose larvae (BSFL) can convert industrial organic waste into biomass for animal feed. BSFL have been known for their utility in converting various forms of biological material waste into insect biomass (Kumar *et al*., 2021; Liu *et al*., 2022; Siddiqui *et al*., 2022). BSFL have a high capacity to bioconvert organic waste while releasing low amounts of greenhouse gases (Liu *et al*., 2021; Luperdi *et al*., 2023; Pang *et al*., 2020), marking their potential as a future alternative animal feed source (English *et al*., 2021; Higa *et al*., 2021; Nugroho and Nur, 2018; Wang and Shelomi, 2017). Additionally, rearing BSFL is considered a sustainable method to convert several types of waste biogenically (Nugroho *et al*., 2023; Santoso *et al*., 2023). BSFL have a high protein content of about 559.9 grams per kilogram (g/kg), crude lipids of about 18.6 g/kg, and a favourable amino acid balance (Al-Qazzaz *et al*., 2016). To raise BSFL, a high-nutrient, low-cost substrate is needed, such as PKM, although this lacks adequate nutrition. Inexpensive substrates that are rich in nutrients are used to boost BSFL development. Alternative methods, such as fermentation, may help to degrade cellulose wastes into usable ingredients for BSFL cultivation. The BSFL may be collected as they reach maturity and utilized as a source of protein and lipids. Insect meal made from larvae may be fed to livestock, and the larvae's lipid supply can also be transesterified into biodiesel to contribute to meeting the world's energy needs (Raksasat *et al*., 2020). Many different substrates and methods have been tried to raise BSFL to achieve the optimum nutrient, protein, and fat values (Fitriana *et al*., 2022; Lalander *et al*., 2020; Shumo *et al*., 2019). Previous research has shown that the nutritional content of palm industry waste might be enriched by fermentation, leading to better BSFL growth. At the best inoculum proportion of 0.5 millilitres (mL) per 10 grams (g) dry weight of palm industry waste, BSFL were 34 percent (%) heavier than the control and had high lipid content (24.7%) and protein value (24.7%) (Liew *et al*., 2022). The average individual weight of BSFL on fermented waste was 0.0619±0.004 g, which was substantially higher than the average individual weight of BSFL raised on a combination of duck dung and rice straw (0.0614±0.001 g), suggesting that BSFL might be employed as high-efficiency transformation agents in the conversion of organic duck manure to stable compost (Pamintuan *et al*., 2020). In addition, BSFL grown on expired milk substrate had a high probability of survival (96.5%) (Purba *et al*., 2021). BSFL that were reared on PKM waste with added fish pellets and fructose exhibited optimum fatty acid composition without reduced growth or survival (Nugroho *et al*., 2023). Although several studies have been conducted to ascertain the growth and nutrition value of BSFL on different substrates, the differences in growth and nutrient profiles of BSFL that were grown on fermented PKM (*f*PKM) combined with varying types of sugars have not been assessed. In this study, BSFL's efficiency in transforming locally produced *f*PKM with various added sugars into insect biomass was measured on a laboratory scale. These results may contribute to better knowledge of BSFL growth, nutrient composition, and lipid or fatty acid metabolism, illuminating the utility of insect cultivation with PKM waste and added sugar (fructose, glucose, maltose, and sucrose) for fat supply. This study predicted that the addition of various sugars would improve the growth and nutritional value of the BSFL and, in particular, that fructose and glucose would enhance the measured parameters better than other sugars. These findings were intended to contribute to BSFL rearing as related to the feed industry. This study was conducted in the Animal Physiology Development and Molecular Laboratory, Faculty of Mathematics and Natural Sciences, Mulawarman University, Samarinda, East Kalimantan, Indonesia, in 2023.

MATERIALS AND METHODS

Chemicals and BSFL source

The chemical substances (analysis grade) were bought from Merck KGaA (Darmstadt, Germany) and Sigma-Aldrich (Sigma Aldrich Incorporation, United State of America). Black soldier fly eggs were provided by a local farmer of BSFL, Ahasa, Samarinda, Limited (Ltd), East Kalimantan, Indonesia). After 4 days, the BSF eggs became young larvae. The young larvae were raised in a plastic growing chamber at about 28 degrees Celsius (°C) and a relative humidity of 60–70% until day 7. Broiler chicken pellets were used as the feeding medium during this stage.

Diet setup and trials

The PKM was obtained from Manunggal, Ltd., which is located in Kalimantan Timur, Indonesia. The PKM was fermented with effective microorganisms 4 (EM4) and the resulting feed was used as the control diet (*f*PKM). The fermentation process was performed by mixing 180 g of molasses, 279 mL of EM4, and 2.5 L of water with 2.5 kg of PKM. This mixture was placed in a plastic bag that was tied tightly closed. The mixture was allowed to stand for 4 days at room temperature to allow the fermentation process to proceed. This fermentation process may have decreased the fibre content of the PKM, as indicated by the reduction of the carbohydrate content from 60.11% to 38.69%, making the *fPKM* more digestible for the BSFL. The data about unfermented PKM were obtained from a previous study (Nugroho *et al*., 2023), while the fermented PKM data were derived from this experiment (Table 1). The treatment diets were formulated with *f*PKM to which various sugars (fructose (*f*PKMfru), glucose (*f*PKMglu), maltose (*f*PKMmal), and sucrose (*f*PKMsuc)) were added. Each sugar was added to the *f*PKM at a proportion of 5%. Based on previous studies, a 5% fructose proportion was the optimum level of added sugar for optimum BSFL growth and nutrient profile (Nugroho *et al*., 2023). Approximately 3,000 7-day-old BSFL were randomly split into five groups of three plastic chambers measuring 24x15x6 centimetres (cm) (length x width x height), each containing 200 larvae. Five different feeding experiments were run in triplicate in these containers. Water was added to each of the substrates to obtain the desired humidity level of 60–70%. In the BSFL rearing chamber room, the temperature was kept at about 28°C. During the experiment, an amount of substrate was given and adjusted to the BSFL in each chamber as described in a prior study with modifications (Hoc *et al*., 2020). On days 10–22, the BSFL were given 1 kilogram (kg) of adjusted substrate. This continued until 90% of the larvae became prepupa, which occurred at about day 22. The growth and survival of the BSFL were assessed on the final day of the experiment. The initial proximate analysis and mineral values of each substrate are shown in Tables 1 and 2.

BSFL growth

The body weight (g) and length (cm) of 30 BSFL that were randomly selected from each chamber were measured on the final day of the study using a digital microscale (Sartorius, Beijing, China) and digital

Table 1: Proximate analysis of initial substrates for BSFL rearing

Proximate analysis (%, as-is basis)	*f*PKM	*f*PKMfru	*f*PKMglu	*f*PKMmal	*f*PKMsuc
Crude protein	11.65	9.25	9.26	9	9.6
Crude fat	4.6	6.69	2.35	2.69	2.44
Ash	3.57	2.95	2.8	2.72	2.83
Moisture	41.49	47.37	48.02	45.84	46.41
Carbohydrate	38.69	33.74	37.57	39.75	38.72

*f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of sugars were added at level 5% into *f*PKM.

Table 2: Mineral value of initial substrates for BSFL rearing

Mineral (%, as-is basis)	*f*PKM	*f*PKMfru	*f*PKMglu	*f*PKMmal	*f*PKMsuc
Phosphorous (P)	0.39	0.4	0.41	0.4	0.4
Calcium (Ca)	0.48	0.48	0.47	0.47	0.47
Potassium (K)	0.75	0.75	0.75	0.74	0.75
Magnesium (Mg)	0.04	0.04	0.04	0.04	0.04
Sodium (Na)	0.17	0.18	0.18	0.16	0.15
Iron (Fe)	57.5	57	57	57.5	57

*f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of sugars were added at level 5% into *f*PKM.

callipers (Tools, Ltd., Shanghai, China).

Proximate analysis

On the final day of the study, all of the BSFL in each group were milled after they were freeze-dried for 72 hours. To evaluate the dry matter content of pre-dried samples, they were dried at 103°C for 16 hours. Subsequently, a three-hour incineration process was conducted at a temperature of 550°C to ascertain the ash composition of each group. The Kjeldahl technique was employed to determine the total nitrogen content (Marco *et al*., 2021; Scheiner, 1976). The crude fat value was measured using the hydrolysis method in HCl and subsequent extraction in light petroleum.

Mineral profiling

The concentrations of minerals, including P, Ca, K, Mg, Na, and Fe, were quantified from the BSFL substrate and the BSFL after they were reared for 22 days on *f*PKM with various types of sugar added. The samples were ashed at a temperature of 500°C for 5 hours to achieve a steady weight. A muffle furnace (BF-02/15, SM Indo, Banten, Indonesia) was used for this procedure. After ashing, the samples were allowed to cool to ambient temperature. Then, a volume of 5 mL of a 1 molar (M) solution of nitric acid (HNO_3) was introduced. The resulting solution was subjected to filtration and transferred into a volumetric flask with a capacity of 100 mL that had been filled to its maximum capacity with a solution of 1M HNO_3. The mineral value was quantified with an atomic absorption spectrophotometer (Model AA6300, Shimadzu, Japan).

Fatty acid profiling

The frozen samples of BSFL were subjected to freeze-drying until a consistent weight was achieved. This was followed by lipid extraction with the direct methylation procedure (Ramos-Bueno *et al*., 2016). The fatty acid value of the samples was evaluated by subjecting them to methylation with 14% of boron trifluoride (BF3) to produce fatty acid methyl esters (FAME). Gas-liquid chromatography was performed with an Agilent 7890A instrument equipped with a DB-23 column at 30 metres (m) in length, 0.25 millimetres (mm) in diameter, and 0.20m of film thickness. The chromatographic analysis was conducted under the specified conditions. The term 'injection' refers to the process of introducing a substance, typically a liquid. The experimental setup consisted of a system with a volume of 1 litre (L). The inlet heater was set at 260°C, and the split ratio was maintained at 35:1. The detector heater was operated at 280°C. The hydrogen and airflow rates were set at 40 millilitres per minute (mL/min) and 400 mL/min, respectively. A purge flow of 25 mL/min was used. The gas used in the experiment was of 99.999 per cent purity. Atmospheric pressure was measured at 0.4 megapascals (MPa), while the nitrogen (N_2) pressure ranged from 0.5 to 0.8 MPa, and the hydrogen (H_2) pressure ranged from 0.3 to 0.4 MPa. The fatty acid composition was determined by calculating the fraction of identified fatty acids.

Statistical analysis

All quantitative data obtained are represented as average ± standard error mean (SEM). A one-way analysis of variance (ANOVA, performed with SPSS software, USA) was applied to evaluate statistical differences and Duncan's multiple-range post-hoc test (DMRT) at a significance of $p<0.05$ (Samimi and Nouri, 2023) was used to assess differences in significance among the experimental groups. Microsoft Excel 2022 (Microsoft Inc., USA) was used to depict graphical data.

RESULTS AND DISCUSSION

In recent decades, numerous industries have produced large amounts of waste due to human activity and rapid population expansion. According to past studies, 3.4 billion metric tonnes of solid trash are expected to be produced globally by 2050. To address trash disposal, authorities must immediately create low-cost, effective technologies that are environmentally friendly (Samimi and Shahriari-Moghadam, 2023). However, thus far, only 20% of waste is recycled, while the rest is landfilled. Waste presents a serious hazard to people, animals, and the environment when it is simply dumped in open-air landfills in poor nations (Ashokkumar *et al*., 2022). One of the waste products that can potentially affect the environment is PKM from the palm oil industry. Previous studies have mentioned that palm kernel meal, both fermented and unfermented, has been studied for its effects on the growth performance of broiler chickens (Alshelmani *et al*., 2016). BSFL that are reared on bioorganic waste, such as PKM, exhibit high nutritional protein and oil content. Compared to other substrates, such as food waste (Fu *et al*., 2022) or manure (Awasthi *et al*., 2020), PKM is a much more promising substrate. PKM as a BSFL substrate has lower potential pathogenicity and bioplastic contamination. The BSFL reared on PKM also offer higher nutritional value than those raised on other substrates. This study evaluated the effects of *f*PKM substrate with various added sugars on BSFL growth and nutritional composition. The weight and length of the BSFL fed *f*PKM with added sugars for 22 days can be seen in Figs. 1 and 2. The addition of various sugars in *f*PKM had no significant effect on the final weight of the BSFL, while the addition of glucose to the *f*PKM resulted in a final BSFL length (1.64 cm) that was significantly ($p<0.05$) higher than the lengths of the BSFL fed on other media.

The study of various sugar additions to insects' diets has been limited. Nevertheless, dipteran larvae, such as BSFL, appear capable of sustaining growth even when provided with diets lacking or low in carbohydrates or sugar. This is attributed to the insects' ability to derive the necessary energy for maintenance and weight increase from proteins (Brookes and Fraenkel, 1958). In this study, the various types of added sugar did not affect the final weight of the BSFL. This finding is supported by past studies that reported that the inclusion of monosaccharides, disaccharides, and starches did not have any significant effect on the growth indices

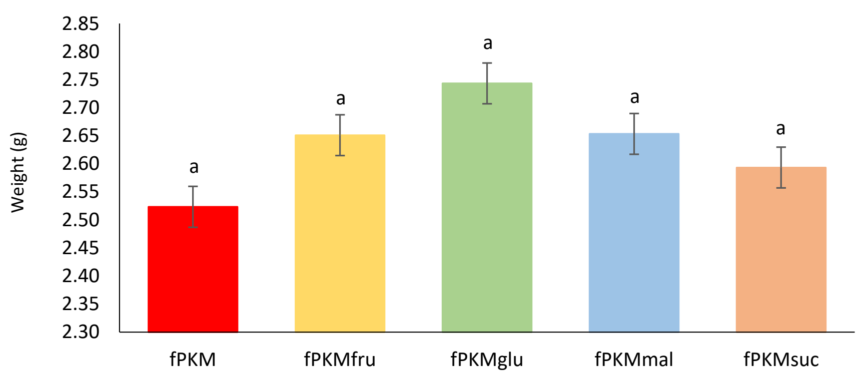

Fig. 1: Mean±SE weight of BSFL fed fermented palm kernel meal (*f*PKM) with various types of sugars at level 5% (fru = fructose; glu = glucose; mal = maltose; suc = sucrose) for 22 days

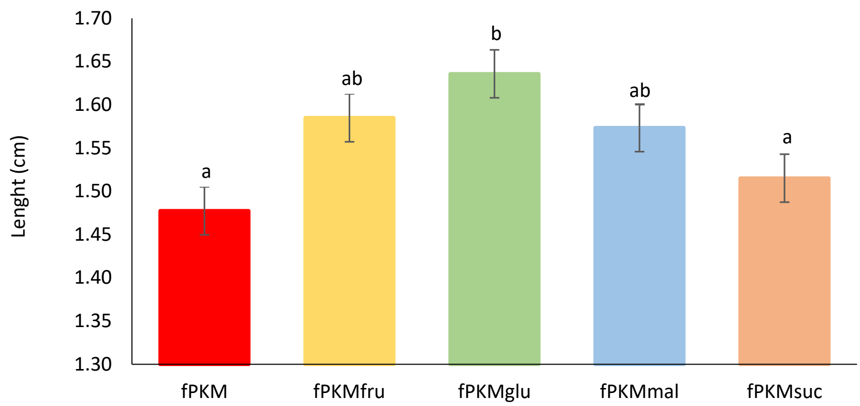

Fig. 2: Mean±SE length (cm) of BSFL after 22 days grown in fermented palm kernel meal (*f*PKM) with various types of sugars (fru = fructose; glu = glucose; mal = maltose; suc = sucrose). Various types of sugars were added at level 5% into *f*PKM. Significant differences (*P<0.05*) among the groups are exhibited by different letters (a, b) in each bar

Table 3: Proximate value of BSFL meal grown in fermented palm kernel meal (*f*PKM) added various sugar for 22 days

Proximate analysis (%, as-is basis)	*f*PKM	*f*PKMfru	*f*PKMglu	*f*PKMmal	*f*PKMsuc
Crude protein (%)	50.66 ± 0.39^{b}	52.26 ± 0.29^{c}	49.90 ± 0.33^{ab}	49.35 ± 0.48^{a}	50.65 ± 0.02^{ab}
Crude fat (%)	19.85 ± 0.05^{a}	20.75 ± 0.06^{b}	20.63 ± 0.04^{b}	20.64 ± 0.02^{b}	20.63 ± 0.04^{b}
Carbohydrate (%)	16.50 ± 0.36^{b}	12.41 ± 0.33^{a}	15.98 ± 0.28^{b}	16.60 ± 0.42^{b}	16.12 ± 0.20^{b}
Ash (%)	11.47 ± 0.01^{a}	11.65 ± 0.06^{b}	11.54 ± 0.01^{a}	11.73 ± 0.03^{b}	11.84 ± 0.03^{c}
Moisture (%)	1.51 ± 0.01^{a}	2.92 ± 0.04^{d}	1.95 ± 0.03^{c}	1.69 ± 0.04^{b}	1.91 ± 0.01^{c}

Data shown as average ± SEM (standard error mean). Significant differences between groups (*P < 0.05*) is indicated by different superscripts following the average± SEM in the same row. *f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of carbohydrate were added (5%) into *f*PKM.

of BSFL (Cohn *et al*., 2022). The addition of sugars, such as galactose or xylan, resulted in a decrease in crude lipid levels. This suggests that the presence of various types of sugar in the diet of BSFL does not induce growth but may affect their proximate and fatty acid values.

Proximate analysis

The BSFL reared on *f*PKM with added fructose showed significantly higher (p<0.05) crude protein and moisture values but had the significantly lowest (p<0.05) ash and carbohydrate values compared to BSFL in other groups. The addition of any type of sugar to the *f*PKM did not significantly affect the BSFL crude fat value compared to other sugar-added substrates but increased it compared to the BSFL reared on unaltered *f*PKM (Table 3).

The use of the *f*PKM with various sugar additions resulted in the biosynthesis of a substantial amount of crude protein, between 49.35±0.48% and 52.26±0.29%, in the BSFL meal. This study's results suggest that *f*PKM with added fructose as a BSFL substrate that is fed for 22 days produces larvae with a significantly higher protein value than the other tested substrates. The crude protein level of the BSFL in this study exhibited similarities to the defatted BSFL meal from BSFL cultivated on food waste, which may contain various sugars (Ebeneezar *et al*., 2021). Similar findings were reported in a previous study, which found that the addition of fructose to PKM resulted in high protein values in the BSFL (Nugroho *et al*., 2023). This high protein content was notably greater than the protein content seen in BSFL produced using industrial agriculture waste products (39–48%) (Zulkifli *et al*., 2022), as well as those reared on rice straw (34.62%) (Pamintuan *et al*., 2020). BSFL are often reared on a substrate of organic waste to achieve a substantial protein yield (Kishawy *et al*., 2022). The considerable protein content found in BSFL makes them a viable alternative to fish meal.

This substitution is particularly advantageous given fish meal's higher cost, limited availability, and unsustainable nature. Recently, there has been a growing trend in the aquafeed business towards partially or completely substituting fish meal with other high-protein sources, such as BSFL meal (Mikołajczak *et al*., 2022; Opiyo *et al*., 2023; Zhao *et al*., 2023). The findings of this study affirm that growing BSFL on *f*PKM with or without added sugar may be a viable approach to implementing BSFL farming in the feed business. Notably, the addition of any type of sugar to the *f*PKM substrate for BSFL resulted in significantly higher amounts of crude fat content, from 20.63±0.04% to 20.75±0.06%, compared to BSFL reared on unaltered *f*PKM. One possible method by which sugars such as fructose, glucose, maltose, and sucrose may increase BSFL fat content is by influencing an insect gene for lipid metabolism that is related to lipid synthesis through a de novo pathway (Bergstrom, 2023; Biolchini *et al*., 2017; Thompson and Redak, 2000; Van Handel, 1966). However, the inclusion of fructose in the *f*PKM reduced the carbohydrate content in the BSFL. When sucrose was added to the *f*PKM, a considerable improvement in ash content was seen. The highest moisture content (2.92±0.04%) was observed in BSFL that were reared on *f*PKM with added fructose. The BSFL grown on *f*PKM with added maltose or sucrose exhibited a significantly higher accumulation of phosphorus, sodium, and iron than those of other groups. Calcium and potassium were accumulated better in the BSFL reared on *f*PKM with added either glucose, maltose, or sucrose. However, magnesium was only significantly elevated in the BSFL reared on *f*PKM with added sucrose (Table 4).

BSFL can accumulate abundant mineral deposits from a wide range of substrates (Daş *et al*., 2023; Raksasat *et al*., 2020; Shumo *et al*., 2019). The addition of sugar to the BSFL substrate was shown to increase mineral accumulation from PKM, which contains minerals in quantities of 835–6,130 parts per million (ppm) (Alimon, 2004; Bárcena-Gama *et al*., 2022). Furthermore, the BSFL raised on substrates with different added sugars exhibited diverse mineral deposit patterns, indicating a high mineral turnover (Paul *et al*., 2023; Seyedalmoosavi *et al*., 2023). Some previous studies have stated that a high-fructose diet was associated with altered phosphorus metabolism in BSFL. There is also a correlation between fructose consumption and decreased blood phosphorus values (Mayes, 1993; Milne and Nielsen, 2000; Wong, 2022). This study found nine fatty acids in the BSFL raised on *f*PKM with various types of sugar added (Table 5). This finding aligns with past studies, which reported that approximately nine fatty acids were detected in BSFL grown on PKM with added fructose (Nugroho *et al*., 2023). The lauric acid level in BSFL increased (22.60±0.34%) when the BSFL were raised on *f*PKM with added glucose. However, adding glucose to the *f*PKM results in significantly reduced values of linolelaidic (21.47±0.36%), *α*-linolenic (13.68±0.32%), and nervonic (1.21±0.00%) acids compared to other groups of BSFL raised on *f*PKM with other added sugars. The inclusion of sucrose in the *f*PKM significantly improved the values of arachidic (5.025±0.23%), erucic (5.45±0.22%), and docosadienoic (1.89±0.10%) acids. The significantly highest myristoleic acid value (5.50±0.05%) was found in the BSFL reared on *f*PKM with added maltose. However, the BSFL grown on *f*PKM with added maltose and sucrose showed significantly lower palmitoleic acid (25.44±0.39 and 25.41±0.30%, respectively) values than other groups of BSFL fed either unaltered *f*PKM or *f*PKM with added fructose or glucose.

The incorporation of sucrose in the *f*PKM for

Table 4: Mineral value of defatted BSFL meal reared in fermented palm kernel meal (*f*PKM) and various types of carbohydrate addition for 22 days (n = 3).

Minerals (%, as-is basis)	*f*PKM	*f*PKMfru	*f*PKMglu	*f*PKMmal	*f*PKMsuc
Phosphorus (P)	3.73±0.03^{a}	4.30±0.06^{b}	4.70±0.00^{c}	4.93±0.07^{d}	5.00±0.06^{d}
Calcium (Ca)	1.27±0.03^{a}	2.23±0.03^{b}	3.47±0.03^{c}	3.53±0.03^{c}	3.53±0.03^{c}
Potassium (K)	3.73±0.07^{a}	4.53±0.03^{b}	5.30±0.06^{c}	5.40±0.06^{c}	5.27±0.09^{c}
Magnesium (Mg)	3.27±0.07^{a}	4.47±0.03^{bc}	4.50±0.06^{bc}	4.67±0.03^{cd}	4.63±0.03^{d}
Sodium (Na)	1.73±0.03^{a}	2.13±0.03^{b}	2.63±0.01^{c}	2.50±0.00^{d}	2.63±0.03^{d}
Iron (Fe)	1.00±0.06^{a}	1.53±0.03^{b}	2.47±0.03^{c}	2.63±0.03^{d}	2.63±0.03^{d}

Data shown as average ± SEM (standard error mean). Significant differences between groups (*P < 0.05*) is indicated by different superscripts following the average± SEM in the same row. *f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of carbohydrate were added (5%) into *f*PKM.

Table 5: Fatty acid value (%) of BSFL grown in fermented palm kernel meal (*f*PKM) with various types of sugars addition

Fatty acids	*f*PKM	*f*PKMfru	*f*PKMglu	*f*PKMmal	*f*PKMsuc
Lauric acid (C12:0)	17.02±0.25[a]	19.77±0.28[b]	22.60±0.34[c]	20.68±0.76[b]	19.18±0.541[b]
Myristoleic acid (C14:1)	4.65±0.05[b]	3.83±0.19[a]	4.22±0.19[a]	5.50±0.05[c]	4.07±0.09[a]
Palmitoleic acid (C16:1)	28.51±0.14[b]	28.18±0.33[b]	27.69±0.21[b]	25.44±0.39[a]	25.41±0.30[a]
Linolelaidic acid (C18:2n6t)	23.34±0.05[b]	22.49±0.29[ab]	21.47±0.36[a]	23.52±0.29[b]	21.84±0.52[a]
α-Linolenic acid (C18:3n3)	14.84±0.33[b]	14.02±0.13[ab]	13.68±0.32[a]	13.98±0.57[ab]	14.85±0.07[b]
Arachidic acid (C20:0)	3.08±0.05[a]	3.67±0.12[ab]	3.26±0.19[a]	4.14±0.33[b]	5.025±0.23[c]
Erucic acid (C22:ln9)	4.11±0.06[a]	4.20±0.02[a]	4.21±0.12[a]	3.74±0.22[a]	5.45±0.22[b]
Docosadienoic acid (C22:2)	1.18±0.03[a]	1.25±0.04[a]	1.62±0.267[a]	1.30±0.17[a]	1.89±0.10[b]
Nervonic acid (C24:ln9)	3.24±0.08[d]	2.55±0.18[cd]	1.21±0.00[a]	1.67±0.42[ab]	2.27±0.22[bc]

Data shown as average ± SEM (standard error mean). Significant differences between groups (*P < 0.05*) is indicated by different superscripts following the average± SEM in the same row. *f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of carbohydrate were added (5%) into *f*PKM.

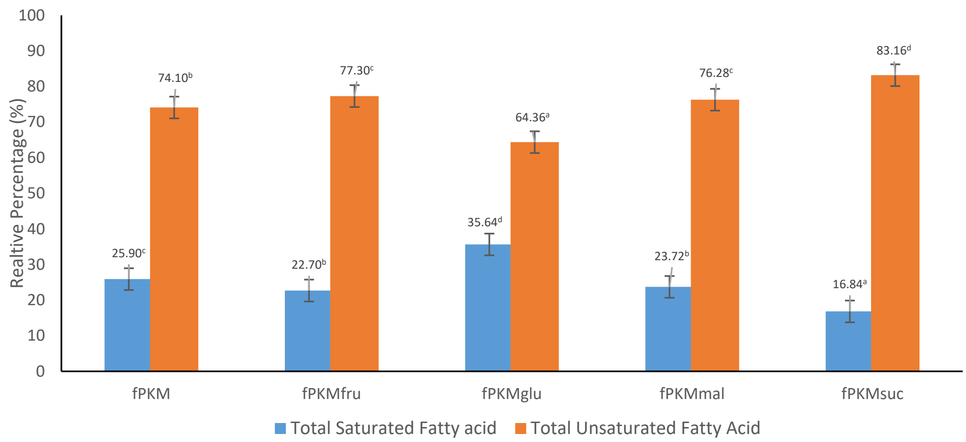

Fig. 3: Relative percentage of fatty acids in the BSFL grown in the fermented palm kernel meal (*f*PKM) added various sugars for 22 days. *f*PKM = Fermented Palm Kernel Meal; fru = fructose; glu = glucose; mal = maltose; suc = sucrose. Various types of sugars e were added at level 5% into fPKM

BSFL resulted in the significantly highest relative percentage of total unsaturated fatty acid (83.16%), but the lowest total saturated fatty acid (16.84%). Conversely, adding glucose to the *f*PKM for BSFL resulted in the significantly lowest relative percentage of total unsaturated fatty acid (64.36%) (Fig. 3).

The lipid content of BSFL may be elevated as a result of sugar in their diets, as the experimental diets boosted the biosynthesis of specific saturated fatty acids, including capric acid (C10), lauric acid (C12), and myristic acid (C14) (Hoc *et al.*, 2020). This study also revealed a notable proportion of certain fatty acids in the BSFL that were grown on *f*PKM. These fatty acids include lauric acid (C12:0), myristoleic acid (C14:1), palmitoleic acid (C16:1), linolelaidic acid (C18:2n6t), *α*-linolenic acid (C18:3n3), arachidic acid (C20:0), erucic acid (C22:ln9), docosadienoic acid (C22:2), and nervonic acid (C24:ln9). Previous studies reported that lauric acid (C12:0) was the predominant fatty acid in BSFL (Nugroho *et al.*, 2023; Shumo *et al.*, 2019), differentiating BSFL from other insect species, such as *Acheta domesticus* (Linnaeus) and *Alphitobius diaperinus* (Pfanzer) (Oonincx *et al.*, 2015). Furthermore, the bioconversion of a significant amount of carbohydrates into lauric acid is attributed to the activity of BSFL (Spranghers *et al.*, 2017). This study demonstrated that the incorporation of glucose into the *f*PKM substrate resulted in an increase in the concentration of lauric acid in the BSFL. Glucose may be involved in fatty acid synthesis via a de novo biosynthesis pathway (Prager *et al.*, 2019; Stanley-Samuelson *et al.*, 1988). The researchers highlighted the possible role of certain enzymes in the metabolic processes to produce BSFL fatty acids. Certain fatty acids, namely decanoic, lauric, and myristic acid, were exclusively detected in deuterated states. Conversely, palmitic, palmitoleic, and oleic acids were observed in both deuterated and non-deuterated forms. This suggests that BSFL can partially synthesize these fatty acids through biosynthetic pathways, rather than solely accumulating them from their diet. Fatty acids play a crucial role in insects by facilitating the synthesis of pheromones for communication and protective compounds (Blomquist *et al*., 2012; Moriconi *et al*., 2019; Pei *et al*., 2019). Furthermore, BSFL oil contains a significant concentration of lauric acid (C12:0), which resembles the composition of coconut oil (Li *et al*., 2016; Ushakova *et al*., 2016). This study also provides evidence that BSFL can efficiently convert *f*PKM with or without added sugars into significant quantities of palmitoleic acid. Dipterans may be distinguished from the members of other insect orders by their elevated palmitoleic acid levels, which often exceed 15% of their total fatty acid composition (Aguilar, 2021). The presence of palmitoleic acid is prevalent in the lipid composition of the larvae of five of the eight species belonging to the order Lepidoptera (Thomas and Kiin-Kabari, 2022). Linolelaidic acid (C18: 2n6t), which is classified as an omega-6 trans fatty acid, was present in significant quantities in the BSFL that were grown on *f*PKM with added glucose. Past research has reported the occurrence of omega-6 trans fatty acids in black soldier fly prepupae (Giannetto *et al*., 2020). The analysis of fatty acids revealed the occurrence of arachidic acid, erucic acid, and docosadienoic acid in the BSFL grown on *f*PKM with added sucrose. This finding is similar to those of previous studies revealing that rearing BSFL on sugar-beet pulp, bakery waste, and fruit and vegetable waste, which may contain sucrose, significantly affects the levels of arachidic acid, erucic acid, and docosadienoic acid present in the BSFL (Fischer and Romano, 2021; Magee *et al*., 2021; Shumo *et al*., 2019). Furthermore, the addition of maltose resulted in a notable increase in myristoleic acid, sometimes referred to as a mono-unsaturated fatty acid (MUFA). Therefore, the incorporation of maltose into BSFL substrate during industrial farming might provide advantageous outcomes in terms of MUFA production, particularly the production of myristoleic acid. The precise mechanisms by which various sugars affect BSFL's fatty acid metabolism remain largely unexplored. Nevertheless, the variation in the fatty acid compositions of BSFL during the prepupal phase may influence the regulation of genes associated with lipid metabolism throughout larval growth (Giannetto *et al*., 2020). Moreover, there are several interconnected pathways linking various types of sugar, especially glucose, and lipid metabolism (Parhofer, 2015).

CONCLUSION

The worldwide rate of organic waste generation is undergoing significant, rapid growth. In the early part of this century, the annual amount of organic waste generated exceeded 600 million tons. According to projections, this quantity is expected to reach about one billion tons by 2025. Palm kernel meal, a byproduct of palm fruit oil extraction, is a significant component of Indonesia's agricultural waste stream. Meanwhile, the oil palm plantation area continues to grow across 22 provinces in Indonesia, covering the nation from east to west. BSFL present an alternative approach to managing organic waste, such as by converting PKM into insect biomass that may then be included in animal feed. The addition of various sugars to *f*PKM is suggested for rearing BSFL to provide nutritional compounds, such as proteins, lipids and various fatty acids, as well as to support mineral accumulation in the BSFL biomass. Specifically, the use of *f*PKM with 5% fructose added to feed BSFL for 22 days improves the final protein content in the BSFL. The addition of sugars to *f*PKM did not significantly affect the final weight of the larvae or the crude fat value, but it did enhance the larvae's crude protein content. The inclusion of glucose resulted in a substantial increase in larval length, as well as an increase in the concentration of lauric acid in the BSFL. However, the addition of glucose to the *f*PKM led to a notable decrease in the relative proportion of total unsaturated fatty acids, such as linolelaidic, α-linolenic, and nervonic acid. Conversely, the addition of fructose resulted in enhanced crude protein and moisture content, while resulting in BSFL that exhibited the lowest levels of ash and carbohydrates of the measured groups. The addition of sucrose to the *f*PKM resulted in significant increases in the BSFL's ash content, magnesium levels, relative percentage of total unsaturated fatty acids, arachidic acid, erucic acid, and docosadienoic acid, as well as phosphorus, sodium, and iron values. The larvae grown on the *f*PKM supplemented with maltose showed improved accumulation of phosphorus, salt, and iron. However, these larvae had a considerably lower value of palmitoleic acid compared to the larvae in other groups. Conversely, the larvae that were grown on *f*PKM supplemented with glucose, maltose, or sucrose exhibited a greater accumulation of calcium and potassium. These findings may be beneficial for feed manufacturers seeking alternatives to fish meal and fish oil. Furthermore, exploring alternative sources of animal feed has become crucial in recent years, and palm kernel waste has emerged as a promising feed alternative option. Palm kernel waste is rich in essential nutrients and is an economical and sustainable feed choice for livestock. Its high fibre content aids digestion, while its protein content contributes to animals' growth and muscle development. Moreover, the use of palm kernel waste as animal feed reduces the environmental impacts associated with the oil processing industry's waste disposal activity. However, certain precautions must be taken, such as proper treatment to remove any harmful substances from PKM before incorporating it into feed. Thus, with proper management and utilization, palm kernel waste presents a valuable resource for animal nutrition, supporting the overall objective of sustainable agriculture.

AUTHOR CONTRIBUTIONS

R.A. Nugroho performed the literature analysis, experimental activities, writing of the manuscript, and analyzed the manuscript critically. R. Aryani contributed in the literature analysis, data, and information collection, and writing of the manuscript. E.H. Hardi performed the data and information collection, data handling, and validation. H. Manurung prepared the experimental activities, data handling, and validation. R. Rudianto performed the experimental activities and writing of the manuscript. W.N. Jati performed the experimental activities, writing of the manuscript and administration.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

°C	Degree Celsius
%	Percent
±	Plus minus
ANOVA	Analysis of Variance
BF3	Boron trifluoride
BSFL	Black soldier fly larvae
C10	Capric acid
C12	Lauric acid
C14	Myristic acid
C14:1	Myristoleic acid
C16:1	Palmitoleic acid
C18:2n6t	Linolelaidic acid
C18:3n3	α–Linolenic acid

C20:0	Arachidic acid
C22:2	Docosadienoic acid
C22:ln9	Eruchic acid
C24:ln9	Nervonic acid
Ca	Calcium
cm	Centimeter
CoA	Coenzyme A
DMRT	Duncan Multiple Range Test
EM4	Effective microorganisms 4
FAME	Fatty acid methyl esters
Fe	Iron
Fig	Figure
fPKM	Fermented palm kernel meal
fPKMfru	Palm kernel meal fructose
fPKMglu	Palm kernel meal glucose
fPKMmal	Palm kernel meal maltose
fPKMsuc	Palm kernel meal sucrose
g	Gram
g/kg	Gram per kilogram
H_2	Hydrogen
HNO_3	Nitric acid
K	Potassium
kg	Kilogram
L	Linnaeus
L	Liter
Ltd	Limited
M	Molar
m	Meter
Mg	Magnesium
mL	Mililiter
mL/g	Mililiter per gram
mL/min	Milliliter per minute
mm	Milimeter
MMT	Million metric ton
MPa	Megapascals
Mt	Metric ton
MUFA	Mono-unsaturated fatty acid
N_2	Nitrogen
Na	Sodium
P	Phosphorous
PKM	Palm kernel meal
ppm	Part per million
SDGs	Sustainable development goals
SEM	Standard error mean
TFA	Trans fatty acid

REFERENCES

Aguilar, J.G.d.S., (2021). An overview of lipids from insects. Biocatal. Agric. Biotechnol., 33: 101967 (**9 pages**).

Al-Qazzaz, M.F.A.; Ismail, D.; Akit, H.; Idris, L.H., (2016). Effect of using insect larvae meal as a complete protein source on quality and productivity characteristics of laying hens. Rev. Bras. de Zootec., 45: 518-523 (**6 pages**).

Alimon, A., (2004). The nutritive value of palm kernel cake for animal feed. Palm Oil Development, 40: 12-14 (**3 pages**).

Alshelmani, M.I.; Loh, T.C.; Foo, H.L.; Sazili, A.Q.; Lau, W.H., (2016). Effect of feeding different levels of palm kernel cake fermented by *Paenibacillus polymyxa* ATCC 842 on nutrient digestibility, intestinal morphology, and gut microflora in broiler chickens. Anim. Feed Sci., 216: 216-224 (**9 pages**).

Angulo-Mosquera, L.S.; Alvarado-Alvarado, A.A.; Rivas-Arrieta, M.J.; Cattaneo, C.R.; Rene, E.R.; García-Depraect, O., (2021). Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives. Sci. Total Environ., 795: 148816 (**15 pages**).

Ashokkumar, V.; Flora, G.; Venkatkarthick, R.; SenthilKannan, K.; Kuppam, C.; Mary Stephy, G.; Kamyab, H.; Chen, W.-H.; Thomas, J.; Ngamcharussrivichai, C., (2022). Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. Fuel. 324: 124313 (**10 pages**).

Austin, K.G.; Mosnier, A.; Pirker, J.; McCallum, I.; Fritz, S.; Kasibhatla, P.S., (2017). Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. Land use policy., 69: 41-48 (**8 pages**).

Awasthi, M.K.; Liu, T.; Awasthi, S.K.; Duan, Y.; Pandey, A.; Zhang, Z., (2020). Manure pretreatments with black soldier fly *Hermetia illucens* L.(Diptera: Stratiomyidae): A study to reduce pathogen content. Sci.Total Environ., 737: 139842 (**13 pages**).

Bárcena-Gama, J.R.; Escobar-España, J.C.; Ley-De Coss, A.; Crosby-Galván, M.M., (2022). Nutrient content and in vitro degradability of the palm kernel meal produced in the state of chiapas, mexico, as feed for ruminants. Agro. Productividad., 5: 125-131 (**7 pages**).

Bergstrom, J.D., (2023). The lipogenic enzyme acetoacetyl-coenzyme a synthetase and ketone body utilization for denovo lipid synthesis, a review. J. Lipid Res., 64(8): 100407 (**18 pages**).

Biolchini, M.; Murru, E.; Anfora, G.; Loy, F.; Banni, S.; Crnjar, R.; Sollai, G., (2017). Fat storage in *Drosophila suzukii* is influenced by different dietary sugars in relation to their palatability. PLoS One, 12: e0183173 (**18 pages**).

Blomquist, G.J.; Jurenka, R.; Schal, C., Tittiger, C. (2012). 12 - pheromone production: Biochemistry and molecular biology. In L. I. Gilbert (Ed.), Insect endocrinology Academic Press. 523-567 **(45 pages).**

Brookes, V.J., Fraenkel, G., (1958). The nutrition of the larva of the housefly, *Musca domestica* L. Physiol. zool., 31: 208-223 (**16 pages**).

Cohn, Z.; Latty, T.; Abbas, A., (2022). Understanding dietary carbohydrates in black soldier fly larvae treatment of organic waste in the circular economy. Waste Manage., 137: 9-19 (**11 pages**).

Cudjoe, D.; Zhu, B.; Nketiah, E.; Wang, H.; Chen, W.; Qianqian, Y., (2021). The potential energy and environmental benefits of global recyclable resources. Sci. Total Environ., 798: 149258 (**15 pages**).

Dahniar, D.; Rusniati, R., (2019). The price analysis of oil palm fresh fruit bunches in PT. Gawi makmur Kalimantan Banjarmasin. Proceeding MICEB (Mulawarman International Conference On Economics and Business), 2: 31-39 (**9 pages**).

Daş, G.; Seyedalmoosavi, M.; Schleifer, K.; Mielenz, M.; Metges, C., (2023). The validity of the bioaccumulation index versus the bioaccumulation factor for assessment of element accumulation in black soldier fly larvae. J. Insects Food Feed, 0(0): 1-16 (**16 pages**).

Dharmawan, A.H.; Mardiyaningsih, D.I.; Komarudin, H.; Ghazoul, J.; Pacheco, P.; Rahmadian, F., (2020). Dynamics of rural economy: A socio-economic understanding of oil palm expansion and landscape changes in East Kalimantan, Indonesia. Land, 9: 213 (**19 pages**).

Ebeneezar, S.; Tejpal, C.; Jeena, N.; Summaya, R.; Chandrasekar, S.; Sayooj, P.; Vijayagopal, P., (2021). Nutritional evaluation, bioconversion performance and phylogenetic assessment of black soldier fly (*Hermetia illucens*, Linn. 1758) larvae valorized from food waste. Environ. Technol. Innov., 23: 101783 (**12 pages**).

Effendi, Z.; Rangkuti, I.U.P.; Muhtadawan, M.I., (2022). Application of boiler fly ash for oil palm kernel separation in claybath. Jurnal Teknik Pertanian Lampung (J. Agric. Eng.), 11(4): 542-548 (**7 pages**).

English, G.; Wanger, G.; Colombo, S.M., (2021). A review of advancements in black soldier fly (*Hermetia illucens*) production for dietary inclusion in salmonid feeds. J. Agric. Food Res., 5: 100164 (**9 pages**).

Fischer, H.; Romano, N., (2021). Fruit, vegetable, and starch mixtures on the nutritional quality of black soldier fly (*Hermetia illucens*) larvae and resulting frass. J. Insects as Food Feed. 7(3): 319-327 (**9 pages**).

Fitriana, E.L.; Laconi, E.B.; Astuti, D.A.; Jayanegara, A., (2022). Effects of various organic substrates on growth performance and nutrient composition of black soldier fly larvae: A meta-analysis. Bioresour. Technol. Rep., 18: 101061 (**8 pages**).

Fu, S.F.; Wang, D.H.; Xie, Z.; Zou, H.; Zheng, Y., (2022). Producing insect protein from food waste digestate via black soldier fly larvae cultivation: A promising choice for digestate disposal. Sci. Total Environ., 830: 154654 (**9 pages**).

Giannetto, A.; Oliva, S.; Lanes, C.F.C.; de Araújo Pedron, F.; Savastano, D.; Baviera, C.; Parrino, V.; Paro, G.L.; Spanò, N.C.; Cappello, T., (2020). *Hermetia illucens* (diptera: Stratiomydae) larvae and prepupae: Biomass production, fatty acid profile and expression of key genes involved in lipid metabolism. J. Biotechnol., 307: 44-54 (**11 pages**).

Hambali, E.; Rivai, M., (2017). The potential of palm oil waste biomass in Indonesia in 2020 and 2030. IOP Conf. Series: Earth Enviro. Sci., 65: 012050 (**10 pages**).

Higa, J.E.; Ruby, M.B.; Rozin, P., (2021). Americans' acceptance of black soldier fly larvae as food for themselves, their dogs, and farmed animals. Food Q. Prefer., 90: 104119 (**7 pages**).

Hoc, B.; Genva, M.; Fauconnier, M.L.; Lognay, G.; Francis, F.; Megido, R.C, (2020). About lipid metabolism in *Hermetia illucens* (L. 1758): on the origin of fatty acids in prepupae. Sci. Reports, 10: 11916 (**8 pages**).

Kishawy, A.T.; Mohammed, H.A.; Zaglool, A.W.; Attia, M.S.; Hassan, F.A.; Roushdy, E.M.; Ismail, T.A.; Ibrahim, D., (2022). Partial defatted black solider larvae meal as a promising strategy to replace fish meal protein in diet for nile tilapia (*Oreochromis niloticus*): Performance, expression of protein and fat transporters, and cytokines related genes and economic efficiency. Aquaculture, 555(11): 738195 (**11 pages**).

Kumar, V.; Fawole, F.J.; Romano, N.; Hossain, M.S.; Labh, S.N.; Overturf, K.; Small, B.C., (2021). Insect (black soldier fly, *Hermetia illucens*) meal supplementation prevents the soybean meal-induced intestinal enteritis in rainbow trout and health benefits of using insect oil. Fish Shellfish Immunol., 109: 116-124 (**45 pages**).

Lalander, C.; Ermolaev, E.; Wiklicky, V.; Vinnerås, B., (2020). Process efficiency and ventilation requirement in black soldier fly larvae composting of substrates with high water content. Sci. Total Environ., 729: 138968 (**10 pages**).

Li, S.; Ji, H.; Zhang, B.; Tian, J.; Zhou, J.; Yu, H., (2016). Influence of black soldier fly (*Hermetia illucens*) larvae oil on growth performance, body composition, tissue fatty acid composition and lipid deposition in juvenile jian carp (*Cyprinus carpio* var. Jian). Aquaculture, 465: 43-52 (**10 pages**).

Liew, C.S.; Wong, C.Y.; Abdelfattah, E.A.; Raksasat, R.; Rawindran, H.; Lim, J.W.; Kiatkittipong, W.; Kiatkittipong, K.; Mohamad, M.; Yek, P.N.Y., (2022). Fungal fermented palm kernel expeller as feed for black soldier fly larvae in producing protein and biodiesel. J. Fungi., 8(4): 332 (**12 pages**).

Liu, T.; Awasthi, S.K.; Qin, S.; Liu, H.; Awasthi, M.K.; Zhou, Y.; Jiao, M.; Pandey, A.; Varjani, S.; Zhang, Z., (2021). Conversion food waste and sawdust into compost employing black soldier fly larvae (Diptera: Stratiomyidae) under the optimized condition. Chemosphere, 272: 129931 (**8 pages**).

Liu, T.; Klammsteiner, T.; Dregulo, A.M.; Kumar, V.; Zhou, Y.; Zhang, Z.; Awasthi, M.K., (2022). Black soldier fly larvae for organic manure recycling and its potential for a circular bioeconomy: A review. Sci. Total Environ., 833: 155122 (**14 pages**).

Liu, Z.; Minor, M.; Morel, P.C.; Najar-Rodriguez, A.J., (2018). Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) larvae. Environ. Entomol., 47: 1609-1617 (**9 pages**).

Luperdi, A.; Flores-Calla, S.; Barriga, X.; Rivera, V.; Salazar, I.; Manrique, P.; Reátegui, J., (2023). Bioprocessing of organic wastes from poultry and bovine slaughterhouses as food substrate for *Hermetia illucens* larval development. Global J. Environ. Sci. Manage., 9: 31-42 (**12 pages**).

Magee, K.; Halstead, J.; Small, R.; Young, I., (2021). Valorisation of organic waste by-products using black soldier fly (*Hermetia illucens*) as a bio-convertor. Sustainability, 13: 8345 (**17 pages**).

Marco, A.; Ramzy, R.R.; Wang, D.; Ji, H., (2021). Sustainable management of se-rich silkworm residuals by black soldier flies larvae to produce a high nutritional value and accumulate ω-3 PUFA. Waste Manage., 124: 72-81 (**10 pages**).

Mayes, P.A., (1993). Intermediary metabolism of fructose. Am. J. Clin. Nutr., 58(5): 754S-765S (**3 pages**).

Milne, D.B.; Nielsen, F.H., (2000). The interaction between dietary fructose and magnesium adversely affects macromineral homeostasis in men. Journal of the American College of Nutrition, 19(1): 31-37 (**7 pages**).

Mikołajczak, Z.; Rawski, M.; Mazurkiewicz, J.; Kierończyk, B.; Kołodziejski, P.; Pruszyńska-Oszmałek, E.; Józefiak, D., (2022). The first insight into black soldier fly meal in brown trout nutrition as an environmentally sustainable fish meal replacement. Animal, 16: 100516 (**8 pages**).

Mohadesi, M.; Gouran, A.; Darabi, F.; Samimi, M., (2023). Sunflower seed pulp ash as an efficient and eco-friendly adsorbent for Congo red uptake: characteristics, kinetics, and optimization. Water Pract. Technol., 18 (**12 pages**).

Moriconi, D.E.; Dulbecco, A.B.; Juarez, M.P.; Calderón-Fernández, G.M., (2019). A fatty acid synthase gene (fasn3) from the integument tissue of *Rhodnius prolixus* contributes to cuticle water loss regulation. Insect Mol. Biol., 28: 850-861 (**12 pages**).

Nugroho, R.A.; Aryani, R.; Hardi, E.H.; Manurung, H.; Rudianto, R.; Wirawan, N.A.; Syalsabillah, N.; Jati, W.N., (2023). Nutritive value, material reduction, biomass conversion rate, and survival of black solider fly larvae reared on palm kernel meal supplemented with fish pellets and fructose. Int. J. Trop. Insect Sci., 43: 1243-1254 (**12 pages**).

Nugroho, R. A.; Nur, F. M. (2018). Insect-based protein: future promising protein source for fish cultured. IOP Conf. Series: Earth Enviro. Sci., 144: 012002. IOP publishing (**8 pages**).

Nugroho, R.A.; Rofiq, M.N.; Santoso, A.D.; Yanuar, A.I.; Hanifa, R.; Nadira, N., (2023). Bioconversion of biowaste by black soldier fly larvae (*Hermetia illucens* L.) for dried larvae production: A life cycle assessment and environmental impact analysis. F1000Res., 12: 814 (**9 pages**).

Oonincx, D.G.; Van Broekhoven, S.; Van Huis, A.; van Loon, J.J., (2015). Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PloS One, 10(12): e0144601 (**20 pages**).

Opiyo, M.A.; Nairuti, R.N.; Ngugi, C.C.; Holeh, G.M. (2023). Black soldier fly (*Hermetia illucens*) larvae meal as a sustainable protein source for fish feed production in kenya. In Emerging sustainable aquaculture innovations in Africa. 89-101 (**13 pages**).

Pamintuan, K.R.S.; Agustin, H.A.T.; Deocareza, E.D., (2020). Growth and nutritional performance of black soldier fly (*Hermetia illucens*) larvae reared in fermented rice straw and duck manure. IOP Conference Series: Earth Environ. Sci., (**9 pages**).

Pang, W.; Hou, D.; Chen, J.; Nowar, E.E.; Li, Z.; Hu, R.; Tomberlin, J.K.; Yu, Z.; Li, Q.; Wang, S., (2020). Reducing greenhouse gas emissions and enhancing carbon and nitrogen conversion in food wastes by the black soldier fly. J. Environ. Manage., 260: 110066 (**8 pages**).

Parhofer, K.G., (2015). Interaction between glucose and lipid metabolism: More than diabetic dyslipidemia. Diabetes Metab. J., 39(5): 353-362 (**10 pages**).

Paul, P.; Awal, M.; Choudhury, M.; Hasan, M.; Rahman, M.; Ahmed, T.; Rahman, M.; Mondal, M., (2023). Evaluation of different food waste for sustainable mass rearing of black soldier fly (*Hermetia illucens* L.) in Bangladesh. J. Insects Food Feed, 9(7): 877-884 (**8 pages**).

Pei, X.J.; Chen, N.; Bai, Y.; Qiao, J.W.; Li, S.; Fan, Y.L.; Liu, T.X., (2019). Bgfas1: A fatty acid synthase gene required for both hydrocarbon and cuticular fatty acid biosynthesis in the german cockroach, *Blattella germanica* (L.). Insect Biochem. Mol. Biol., 112: 103203 (**12 pages**).

Prager, L.; Bruckmann, A.; Ruther, J., (2019). De novo biosynthesis of fatty acids from α-d-glucose in parasitoid wasps of the nasonia group. Insect Biochem. Mol. Biol., 115: 103256 (**28 pages**).

Purba, I.J.; Kinasih, I.; Putra, R.E., (2021). Growth of black soldier (*Hermetia illucens*) larvae fed with expired powder milk and rotten avocado. Biotropika J. Trop. Biol., 9(1): 88-95 (**8 pages**).

Raksasat, R.; Lim, J.W.; Kiatkittipong, W.; Kiatkittipong, K.; Ho, Y.C.; Lam, M.K.; Font-Palma, C.; Mohd Zaid, H.F.; Cheng, C.K., (2020). A review of organic waste enrichment for inducing palatability of black soldier fly larvae: Wastes to valuable resources. Environ. Pollut., 267: 115488 (**17 pages**).

Ramos-Bueno, R.P.; González-Fernández, M.J.; Sánchez-Muros-Lozano, M.J.; García-Barroso, F.; Guil-Guerrero, J.L., (2016). Fatty acid profiles and cholesterol content of seven insect species assessed by several extraction systems. Eur. Food Res. Technol., 242: 1471-1477 (**7 pages**).

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 (**12 pages**).

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 (**10 pages**).

Samimi, M.; Shahriari-Moghadam, M., (2023). The Lantana camara L. stem biomass as an inexpensive and efficient biosorbent for the adsorptive removal of malachite green from aquatic environments: kinetics, equilibrium and thermodynamic studies. Int. J. Phytoremediation, 25(10): 1328-1336 (**9 pages**).

Santoso, A.D.; Handayani, T.; Nugroho, R.A.; Yanuar, A.; Nadirah, N.; Rohaeni, E.; Widjaja, E.; Oktaufik, M.; Ayuningtyas, U.; Erlambang, Y., (2023). Sustainability index analysis of the black soldier fly (*Hermetia illucens*) cultivation from food waste substrate. Global J. Environ. Sci. Manage., 9: 851-870 (**20 pages**).

Scheiner, D., (1976). Determination of ammonia and kjeldahl nitrogen by indophenol method. Water Res., 10: 31-36 (**6 pages**).

Seyedalmoosavi, M.M.; Manfred M.; Kai S.; Solvig G.; Petra W.; Jens T.; Liane H.; Sven D.; Gürbüz D.; Cornelia C.M, (2023). Upcycling of recycled minerals from sewage sludge through black soldier fly larvae (*Hermetia illucens*): Impact on growth and mineral accumulation. J Environ Manage., 344: 118695 (**12 pages**).

Sharma, V.; Anyanwu, C.; Braccio, G.; Akubuo, C., (2005). Palm oil (*Elaeis guiniensis*) plantations: A potential feedstock for biodiesel production, in Nigeria. Int. Energy J., 6(2): 69-82 (**14 pages**).

Shumo, M.; Osuga, I.M.; Khamis, F.M.; Tanga, C.M.; Fiaboe, K.K.; Subramanian, S.; Ekesi, S.; van Huis, A.; Borgemeister, C., (2019). The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. Sci. Rep., 9: 1-13 (**12 pages**).

Siddiqui, S.; Snoeck, E.; Tello, A.; Alles, M.; Fernando, I.; Saraswati, Y.; Rahayu, T.; Grover, R.; Ullah, M.; Ristow, B., (2022). Manipulation of the black soldier fly larvae (*Hermetia illucens*; diptera: Stratiomyidae) fatty acid profile through the substrate. J. Insects Food Feed, 8(8): 837-855 (**19 pages**).

Siddiqui, S.A.; Ristow, B.; Rahayu, T.; Putra, N.S.; Yuwono, N.W.; Mategeko, B.; Smetana, S.; Saki, M.; Nawaz, A.; Nagdalian, A., (2022). Black soldier fly larvae (BSFL) and their affinity for organic waste processing. Waste Manage., 140: 1-13 (**13 pages**).

Spranghers, T.; Ottoboni, M.; Klootwijk, C.; Ovyn, A.; Deboosere, S.; De Meulenaer, B.; Michiels, J.; Eeckhout, M.; De Clercq, P.; De Smet, S., (2017). Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. J. Sci. Food Agric., 97: 2594-2600 (**7 pages**).

Stanley-Samuelson, D.W.; Jurenka, R.A.; Cripps, C.; Blomquist, G.J.; de Renobales, M., (1988). Fatty acids in insects: Composition, metabolism, and biological significance. Arch. Insect Biochem. Physiol., 9: 1-33 (**34 pages**).

Thomas, C.; Kiin-Kabari, D., (2022). Comparative study on fatty acid profiles of selected edible insects and animals in africa: A review. Int. J. Agric. Earth Sci., 8: 40-52 (**13 pages**).

Thompson, S.; Redak, R., (2000). Interactions of dietary protein and carbohydrate determine blood sugar level and regulate nutrient selection in the insect *Manduca sexta* L. Biochim. Biophys. Acta Gen. Subj., 1523: 91-102 (**12 pages**).

Ushakova, N.; Brodskii, E.; Kovalenko, A.; Bastrakov, A.; Kozlova, A.; Pavlov, D., (2016). Characteristics of lipid fractions of larvae of the black soldier fly *Hermetia illucens*. Dokl Biochem. Biophys., 468(4): 462-465 (**4 pages**).

Van Handel, E., (1966). Temperature independence of the composition of triglyceride fatty acids synthesized de novo by the mosquito. J. Lipid Res., 7: 112-115 (**4 pages**).

Wang, Y.S.; Shelomi, M., (2017). Review of black soldier fly (*Hermetia* *illucens*) as animal feed and human food. Foods. 6: 91 (**23 pages**).

Widyarsana, I.M.W.; Al Furqan, R.; Budhicahyanto, M.; Saraswati, D.; Nurfajri, N., (2021). Evaluation of existing and future zero waste approach in municipal solid waste management utilizing the zero waste index: Bali province, Indonesia. Preprint. 1: 1-17 (**17 pages**).

Wong, S.K., (2022). A review of current evidence on the relationship between phosphate metabolism and metabolic syndrome. Nutrients, 14: 4525 (**27 pages**).

Zhao, J.; Ban, T.; Miyawaki, H.; Hirayasu, H.; Izumo, A.; Iwase, S.-i.; Kasai, K.; Kawasaki, K., (2023). Long-term dietary fish meal substitution with the black soldier fly larval meal modifies the caecal microbiota and microbial pathway in laying hens. Animals, 13: 2629 (**16 pages**).

Zulkifli, N.F.N.M.; Seok-Kian, A.Y.; Seng, L.L.; Mustafa, S.; Kim, Y.S.; Shapawi, R., (2022). Nutritional value of black soldier fly (*Hermetia illucens*) larvae processed by different methods. PloS one, 17(2): e0263924 (**14 pages**).

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ORIGINAL RESEARCH PAPER

Photochemical oxidation and landfarming as remediation techniques for oil-contaminated soil

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ABSTRACT

BACKGROUND AND OBJECTIVES: With technological advances, mining industries use more crude oil and its products. Finding fast, effective, and eco-friendly repair techniques for oil-contaminated soil is crucial. Clay–titanium dioxide/manganese was used to investigate how oil breaks down in soil under sunlight. Various soil remediation techniques have been used to discard oil pollutants in soil. A polluted site must be cleaned effectively with a suitable method. Natural attenuation takes too long to produce positive results, whereas landfarming can produce toxic intermediates due to the organisms' inability to degrade other oil components. Photochemical oxidation is a promising eco-friendly technique that can be employed as an alternative remediation method. The speed at which natural attenuation, photochemical oxidation, and landfarming could remove oil from contaminated soils was examined. Photochemical oxidation's superiority as a remediation technique over landfarming is hypothesized.

METHODS: Using clay modified with titanium dioxide and manganese, the effectiveness of landfarming and photochemical oxidation on oil-contaminated soil was investigated, together with the processes' kinetics. To establish the processes' effectiveness and kinetics, the oil residue was calculated at 7-day intervals for 35 days.

FINDINGS: Initial oil concentration was 56.6 milligrams per kilogram, and degradation rates ranged from 23.91-80.47 percent. Highest oil reduction was 10.86 milligrams per kilogram. Combined remediation (biocarb and grafted clays) produced high degradation rate constants, k (0.046-0.049/day) and low degradation half-lives, t½ (15.2, 17.4 days). Photochemical oxidation rate constants ranged from 0.015-0.03984/day and half-lives ranged from 17.395-44.971 days, whereas landfarming had a rate constant of 0.008 and half-life of 83.094. Natural attenuation had the lowest k (0.007) and longest half-life (t½) of 94.8 days. Significant differences in means were observed among treatments (control, biocarb, and bicarb + grafted clays) at $p \leq 0.05$, suggesting that treatment caused oil decrease in microcosms for biocarb + grafted clays. Grafted clays plus biocarb show potential for combined remediation of oil-contaminated soil.

CONCLUSION: One primary indicator used to assess treatments' efficacy is oil reduction, calculated using difference in oil content in soil before and after remediation. This shows that oil can be quickly removed from oil-contaminated soil by using biocarb + grafted South Luangwa with 80 percent oil reduction. Results suggest that photochemical oxidation may be used to effectively degrade oil and shorten remediation time. Photochemical oxidation is environmentally friendly and degrades oil faster than landfarming. Zambia's Mopani Copper Mines can consider adopting photochemical oxidation as a remediation technique in treating oil-contaminated soil.

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INTRODUCTION

The entire world relies on crude oil as a clean energy source, which ultimately encourages widespread exploration, refining, transportation, and consumption of crude oil-derived goods (Khudur *et al.*, 2015; Sharifi, 2022). As one of the primary sources of fuel, crude oil continues to have an impact on numerous nations. The degree to which life has become easier in contemporary communities because of the oil, which is simple to use and locate, cannot be overemphasized. However, it is impossible to overlook the pollution it causes, particularly soil degradation when used in sectors such as mining, transportation, and the oil and gas industry. Alkanes or paraffins with 1 to 40 carbon (C) atoms per molecule make up the majority of oil wastes, whereas some crude oil may also contain significant amounts of polyaromatic hydrocarbons (PAHs) (Imam *et al.*, 2019). PAHs tend to adsorb on solid particles due to their hydrophobic and recalcitrant properties, which makes them one of the main soil contaminants (Thacharodi *et al.*, 2023). These oil wastes are produced by the petroleum industry, auto repair shops, oil cleaning facilities, and other industries. To reduce harmful environmental consequences and the risk to human health posed by oil wastes, which can become pollutants in soil, sediment, and water, extensive efforts are being made to remediate them (Kebede *et al.*, 2021; Samimi and Shahriari Moghadam, 2020). The United States Environmental Protection Agency (USPA) classifies them as priority environmental contaminants due to their toxicity, mutagenic and carcinogenic properties, as well as their persistence in the environment, which may have an impact on human health and the ecosystem (Michael-Igolima *et al.*, 2022). Soil contamination from crude oil and petroleum products is now a serious problem for the environment because of the potential consequences for the ecosystem and human health (Naeem and Qazi, 2020). Spilt oil and waste products from the petrochemical and petroleum sectors are major sources of environmental pollution that have affected local ecosystems and their inhabitants. This oil can have persistent sub-acute toxicological effects, which can change population dynamics and disturb trophic relationships and the structure of natural communities within ecosystems (lower growth and reproduction, poor health, low recruitment rates, etc.) (Aichner *et al.*, 2013). The immediate repercussions of these oil spills include the death of animals and plants and the disruption of food chains and ecology. The long-term effects include birth abnormalities and genetic changes (Akinwumiju *et al.*, 2020). Even though crude oil is not categorized as a hazardous chemical, it is nonetheless regarded as persistent due to its derivatives, which have the potential to bioconcentrate and bioaccumulate in food chains (Shaker and Almukhtar, 2016). The introduction of crude oil into the ecosystem has affected the health of people, plants, and animals because the majority of its elements are carcinogenic and cause more than 0.005 billion deaths annually (Idowu *et al.*, 2019). Oil pollution has terrible consequences on the soil because it changes the microbial population, the structure and content of organic matter in the soil, and the enzymatic activities that take place there (Yang *et al.*, 2017). This hinders plant growth and development. Waste oil contaminates surface and groundwater systems by adhering to soil components and is typically difficult to remove or degrade (Michael-Igolima *et al.*, 2022). The presence of crude oil in the soil causes the environment to become anaerobic by obstructing the flow of air, which has an impact on the microbial populations in the soil (Sutton *et al.*, 2013). When crude oil spills on land, it limits water absorption by making the soil hydrophobic—it repels water—and when it falls on grass and agricultural fields, it often kills plant life (Brown *et al.*, 2017). Oil spills generate an imbalance in the carbon–nitrogen (C-N) ratio at the spill site because crude oil is mostly made of carbon and hydrogen. This results in phosphorus and nitrogen deficiency in oil-soaked soil, which slows down bacterial growth and carbon source utilization(s) (Agarry *et al.*, 2013; Samimi and Shahriari-Moghadam, 2021). The components of crude oil break down at varying rates, with the heavier compounds such as cycloalkane being more resistant to microbial attack in the soil, whereas the lighter hydrocarbons break down quickly even under abiotic conditions (Abioye *et al.*, 2011). If not removed, spilt crude oil could be retained in soil cavities and build up a significant bank of residual saturation, which could lead to significant groundwater contamination (Dzionek *et al.*, 2016). Additionally, the potential of hydrogen (pH) and total organic carbon (TOC) content of the soil might change when crude oil is added to it (Okoh *et al.*, 2020). The pH varies greatly across a large range and affects solubility in the soil, which therefore affects the availability of different soil elements. When the pH is close to 8, the level of bacterial activity in the soil is improved. The remaining bulk of crude oil becomes denser and less mobile as a result of volatilization and solubilization. As part of the organic matter in the soil, the partially decomposed hydrocarbon is absorbed, creating an asphalt crust that is more difficult to biodegrade (Brown *et al.*, 2017). Finding low-cost environmental clean-up methods to decrease, degrade, or remove the pollutants has become necessary due to the scale of environmental pollution caused by crude oil-related operations. The development of soil remediation methods has received a lot of attention, and several novel and creative approaches to the effective removal of contaminants from soils have been explored to bring the contaminant's contents down to a level that is safe and acceptable (He *et al.*, 2014; Silva-Castro *et al.*, 2013). Landfarming and photochemical oxidation are some of the techniques used in oil remediation (Saneha *et al.,* 2023). In land farming, conventional farming techniques including tilling, bulking (which improves soil uniformity for biodegradation and aeration), irrigation (which supplies moisture), and fertilizer application (Samimi *et al.,* 2023) (provides nutrients to enhance the population of oil degraders) are used. Aspects that restrict its degradation efficiency, including the low number of oil degraders, superficial treatment as 10-35 centimeters (cm) of soil layer, poor contaminant uptake, and low bioavailability offset its unique benefit of promoting the natural bacteria (Sakshi and Haritash, 2019). Because landfarming is an ex-situ remediation method, the contamination is moved to another area for treatment after procedures take place off-site. As a result, unlike other remediation approaches such as photochemical oxidation, which may be done in-situ, it becomes more expensive with increased human participation and direct contact to toxins. Also, because it employs natural microbes to degrade oil, the technique is not always successful because some of them (microbes) cannot degrade some components of oil (Kong *et al.*, 2018). Photochemical oxidation, in contrast, is a process of transforming a chemical compound using sunlight (Hadnadjev-Kostic *et al*., 2014). Ultraviolet or light technique (UV or sunlight) is applied to a mixture of the contaminant and a catalyst, causing the organic pollutants to oxidize and create compounds such as carbon dioxide and water. Semiconductor catalysts consist of an empty conduction band with higher energy and a valence band containing electrons (e^-) that are energetically stable. Exposure of these semiconductors to light triggers photocatalytic reactions by promoting an e^- into the conduction band and creating a hole (h^+) in the valence band (Liu and Zhang, 2014). As a result, hydroxyl ($OH^•$) and superoxide ($O_2^•$) anion radicals are produced through photocatalytic reactions, leading to the photochemical oxidation of oil at the semiconductor surface. Because photochemical oxidation may be performed in situ, unlike landfarming, which typically requires transferring the contaminated soil from one location to be treated in another, it has the potential to be used in big field undertakings. As a result, there is less chance of contamination, less expense, and less human interaction (Kong *et al.*, 2018). According to earlier findings, photooxidation can eliminate all forms of oil-related molecules, indicating that oil constituents can be removed nonselectively (Brame *et al.*, 2013). Removing oil deposits without causing environmental contamination is possible with the use of titanium dioxide (TiO_2)/clay composite. In the process of decomposing oil and other organic pollutants in the soil, this remediation strategy is not adequately used (Wang *et al.*, 2014). The use of modified Zambian clay materials in the remediation of oil-contaminated soil has not been studied. Some components of oil are known to be persisitent and recalcitrant, meaning they might not be degraded by organisms in the soil. As such, the goal of this study was to assess the feasibility of photochemical oxidation using clay materials modified with a nontoxic transition metal and biodegradable silanes in the remediation of oil-contaminated soil. $OH^•$ radicals generated during light illumination are nonselective and therefore can degrade all forms of oil constituents. The primary aim of this study was to determine an alternative or supplement to the landfarming strategy now employed by one of Zambia's biggest copper mines. In particular, a less expensive and speedier method of remediating oil-contaminated soil was sought. It was found that photochemical oxidation was more effective than landfarming in oil degradation. Both landfarming and photochemical oxidation treatment have advantages in that they have a low impact on the environment and are energy efficient, with straightforward technology design and implementation. The current study was carried out at the Copperbelt University and Mopani Copper Mines (MCM), Zambia in 2023.

Table 1: Oxide composition, surface area, and pore volume of the clays

Clay	SiO_2	Al_2O_3	Surface area (m^2/g)	Pore volume (cm^3/g)
UC	52.41	13.89	16.78	0.043
MC	-	-	17.98	0.048
UL	35.08	13.85	50.70	0.059
ML	-	-	64.51	0.068

Fig. 1: MCM spillsorb farm

MATERIALS AND METHODS

Clay additives characterization

The clay samples (both modified and unmodified) were characterized by X-ray fluorescence (XRF), inductively coupled plasma (ICP), Brunauer-Emmett-Teller (BET), and Barret-Joyner-Halenda (BJH). From previous studies, the following properties were determined for the various raw and engineered clay materials used in this study. Table 1 shows a summary of the results previously obtained for the unmodified and modified clays. Elemental composition by XRF and ICP showed that unmodified South Luangwa (UL) had a 2.5 silicon dioxide: aluminum oxide (SiO_2: Al_2O_3) ratio, and 3.8 for unmodified Chingola (UC). The surface area and pore sizes were higher in modified South Luangwa (ML) at 64.5081 square meter per gram (m^2/g) and 0.068 nanometer (nm) compared to modified Chingola (MC) at 17.9780 m^2/g and pore volume at 0.048 cubic centimeter per gram (cm^3/g). Both fourier transform infrared (FTIR) spectra showed and confirmed the presence of grafted hydrophobic silanes, whereas the ultra violet-visible spectroscopy (UV-Vis) confirmed the incorporation of manganese (Mn) because a red shift in energy was observed in both ML at 3.1 e^- volt (eV) and MC at 2.5 eV (Mambwe *et al.*, 2023).

Soil sample collection

Oil-contaminated soil samples were collected from the MCM spillsorb farm (Fig. 1) situated approximately 11 kilometers (km) southeast of Kitwe, Copperbelt Province, Zambia with latitude 12° 48' 13.79''S and longitude 28° 12' 47.30''E. The study area is located in an isolated area where the temperature ranges from approximately 20 degrees Celsius (°C) to 50 °C for purposes of soil remediation. Random sampling was employed during the collection of contaminated soil samples. The samples were collected in a zig-zag pattern across the field. The representative laboratory-size sample was achieved by the quartering method, and the process was repeated several times to ensure proper mixing of the soil. About 10 kilograms (kg) of contaminated soil were collected, and the soil was removed within the band wall from the top of the heap of soil using a shovel and placed in polythene bags, which were later transported to the chemistry laboratory at the Copperbelt University for sample treatment.

Contaminated soil sample preparation

The first step in soil preparation was to let the soil dry naturally for a few days without exposing it to

Fig. 2: Oil-contaminated soil samples

direct sunshine in a clean, well-ventilated laboratory. To speed up the drying process, the aggregated soils were crushed. The soils were cleared of disturbing elements including stones, leaves, and bits of wood. After being dried, the soils were poured through 2 millimeter (mm) sieves. The soils that were retained were crushed once again and sieved. Then, the soils were homogenized by mixing them until oils were assumed to have the same concentration within the soils (Effendi and Aminati, 2019). The prepared samples are shown in Fig. 2.

Soil characterization

To understand how the physical and chemical characteristics of contaminated soil affect the pace of oil breakdown, temperature, moisture content, and pH were determined (Okoh *et al.*, 2020). To determine the pH, 10 grams (g) of air-dried soil was obtained for the test, and 10 milliliter (mL) of reagent water was added and mixed. A pH electrode was then used to measure the supernatant (Lin *et al.*, 2022). The dry-wet method was used to calculate the moisture content (Okoh *et al.*, 2020). The procedure of dry wet involves drying the soil sample and calculating the weight difference between the wet and dry samples to determine the moisture content directly.

Determination of the initial amount of oil in the contaminated soil sample

The solvent extraction method was used to gravimetrically measure the amount of oil present in the contaminated soil sample. A 50 mL flask containing around 10 g of the contaminated soil sample was filled with 20 mL of n-hexane. To allow the hexane to extract the oil from the soil sample, the mixture was violently agitated on a magnetic stirrer for 30 minutes (min). A Whatman filter paper was used to filter the solution, and the liquid phase extract (filtrate) was then diluted by adding 1 mL of the extract to 50 mL of hexane (Almutairi, 2022). During the treatment process, oil content was analyzed with the use of total oil grease/total petroleum hydrocarbon (TOG/TPH) infracal. Ten grams (10 g) of clumpy, damp soil samples were mixed with 5 g of sodium sulphate to prevent water from interfering with the analysis. An extraction ratio of 1:2 was achieved by adding twice the extraction solvent (Horiba S-316) as the soil sample weight. After that, the samples were left on the mechanical shaker for an hour. A Whatman filter paper was used to filter the solvent, which included about 1 g of silica gel, and the solvent was then transferred into a sterile beaker (silica gel is used for the removal of polar organics before TPH analysis) (Fanaei *et al.*, 2020). Using measurements taken, Eq. 1 was applied to calculate the percentage decrease in total oil content (Soliman *et al.*, 2014; Samimi and Safari, 2022).

$$\%R = \frac{(Co - Ce)}{Co} \times 100 \tag{1}$$

where C_o is the initial amount of oil in the soil (at time of 0), C_e is the amount of oil in the soil at time (t), and percent (%)R is the percentage of oil degradation after treatment (Farooq *et al.*, 2022; Hussain *et al.*, 2017).

Determination of total organic carbon

Using the modified wet combustion method, TOC was calculated. The Walkley and Black wet combustion method was used to calculate TOC (Jha *et al.*, 2014). In this procedure, a 250 mL Erlenmeyer conical flask was filled with a 1 g contaminated soil sample. After that, 10 mL of a 0.16 Molar (M) potassium dichromate solution was added to the flask's contents, and the flask was gently shaken to ensure that the contents were thoroughly mixed. The contents of the flask were gently mixed with 20 mL of concentrated sulphuric acid before being left to stand for 5 min under a fume hood. The contents of the flask were then filled with distilled water until the total volume was around 125 mL, and the flask was gently spun. After 30 min, the flask's contents were allowed to cool to room temperature (the addition of sulphuric acid warms the mixture). Thereafter, 1.0 M ferrous sulphate solution was used to titrate the mixture before adding 5 or 6 drops of phenanthroline complex. The color of the solution changed from green to reddish-brown as the titration's endpoint was reached. The same process was used for a blank titration, but without a sample (Jha *et al.*, 2014).

Statistical analysis

A one-way analysis of variance (ANOVA) test was used to compare means of the oil removal treatments performed. A Fisher's least significant difference (LSD) multiple comparison test was also conducted using Statistical Package for Social Sciences (SPSS) software (Sanie Jahromi *et al.*, 2023) version 27 at 95% confidence interval. Fig. 6 was plotted using OriginPro software version 2021. The bar charts (Figs. 4 and 5) were plotted in Microsoft Excel and SPSS respectively. The coefficient of determination (R^2) was used to measure how well the data fit into the statistical model (first-order kinetics model) used in the study.

Treatment of oil-contaminated soil samples

Contaminated soil samples (500 g) were put into 8 different plastic basins (microcosms), and each basin was labeled. The contaminated soil samples were treated with modified clay samples, namely UC and UL. These clay samples were modified by incorporation of TiO_2 and Mn ions, and then part of the modified samples was further modified by grafting with isobutyltrimethoxylsilane to improve their photocatalytic and adsorption properties respectively. Briefly, a beaker filled with 300 mL of ethanol was filled with a 50 g sample of each clay (UC and UL). The samples were weighed and spread to create a slurry, which was left suspended for a full day before being mixed. For 15 min, the slurry was continuously stirred while 10.25 mL of acetylacetone, a complexing agent, was added. One gram (1 g) of manganese (II) nitrate ($Mn(NO_3)_2$) was added, while 16.7 mL of titanium isopropoxide ($Ti(OPr_4)$) was also subsequently added to the reaction mixture. After that, the mixtures were dried for 6 hours at 80 °C in the oven, and then the materials were crushed and calcined for 3 hours at 550 °C. In this study, these clays are referred to as MC and modified UL. Ten grams (10 g) of the modified and calcined clay (MC and ML) were later grafted with 10.75 mL of isobutyltrimethoxylsilane, which was added dropwise under constant stirring for 24 hours after being dispersed in ethanol: water mixture (4:1, volume per volume) (*v*:*v*) in a round bottom flask at room temperature. The mixture was then allowed to react for 3 hours at 110 °C. After filtering, the mixture was cleaned of the unreacted silanes using toluene. Following surface modification, the clays were dried for 4 hours at 50 °C in an oven. These clays were then referred to as grafted Chingola (GC) and grafted South Luangwa (GL) (Mambwe *et al.*, 2023). The prepared contaminated soil samples are shown in Fig. 2. Four different forms of treatment were used, and the water content was kept between 20% and 50% of its water-holding capability (Sihag *et al.*, 2014). The treatments are depicted in Fig. 3 and are explained by the following steps:

1- Natural attenuation

This utilized the natural ability of the soil to break down pollutants. No additives were added, and it served as a control.

2- Landfarming

The experiment under landfarming conditions was done to mimic the treatment method at MCM spillsorb farm where the contaminated soil samples were obtained. In this method, biocarb (B) (nutrients) were included to promote organic biodegradation.

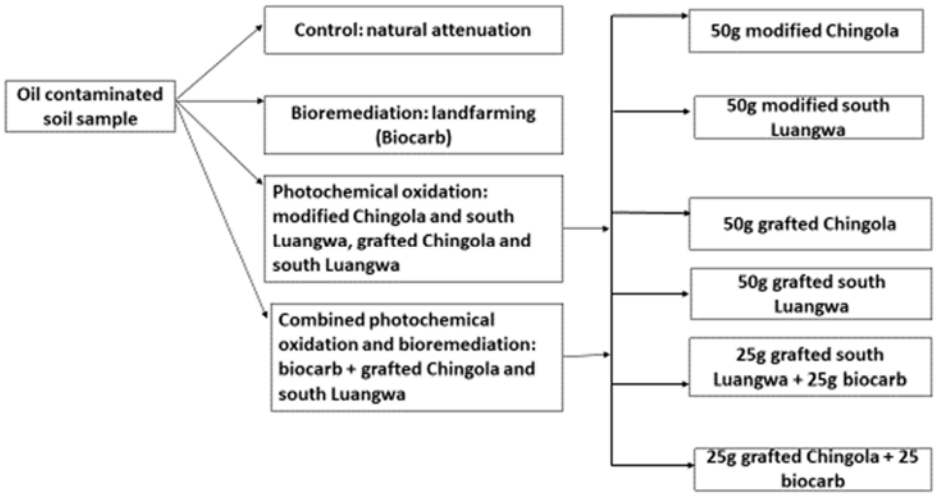

Fig. 3: Contaminated soil sample treatment setup (Effendi and Aminati, 2019)

Table 2: Moisture content and pH values of oil-contaminated soil samples after treatment

Sample	Moisture content (%)	pH values
Control	28.02	5.5
Biocarb	30.84	5.7
MC	35.06	5.8
GC	36.95	6.1
ML	35.73	5.9
GL	38.64	6.6
B+ GC	43.30	6.8
B+ GL	45.58	7.6

Thus, this treatment sample was labeled biocarb.

3- Photochemical oxidation

Modified and grafted clay samples (Chingola and South Luangwa) were added as photocatalysts to aid in the degradation of oil in the soil. The microcosms were labeled according to the method of modification, that is, MC, ML; modified with TiO_2/Mn, GC and GL (modified clay samples grafted with isobutyltrimethoxylsilane).

4- Combined landfarming and photochemical oxidation

Using a combination of biocarb and modified and grafted clay photocatalysts, the treatments were labeled B + GC and B + GL. The amounts of each photocatalyst added to the contaminated soil are shown in Fig. 3. The ratios were adapted from Okonofua *et al.* (2020) and Effendi and Aminati (2019).

All the treatments were subjected to the same controlled conditions in the greenhouse, but they were exposed to sunlight on sunny days. For aeration, each basin's contents were tilled twice a week, and the moisture level was kept at 20-50% by adding water. The frequency of tilling was helpful in improving light penetration (Hadei *et al.*, 2021). For 35 days, 7-day interval sampling from each plastic basin was done to determine how much oil was still present.

RESULTS AND DISCUSSION

Temperature

The physical and chemical parameters of temperature, moisture, and pH were determined because they have an impact on photochemical oxidation and landfarming. The rate of photochemical oxidation is increased by a high temperature caused by a high irradiation intensity (Hadei *et al.*, 2021). The experiments were carried out at temperatures in the range of 25-40 °C, with the ideal temperature being around 40 °C on sunny days. In photochemical oxidation, e^--hole creation predominates in conditions of higher light intensity, and e^--hole recombination is minimal, leading to increased degradation of the

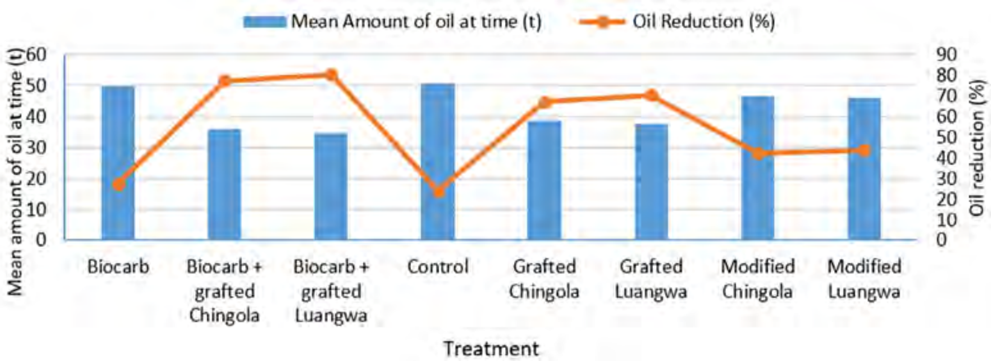

Fig. 4: Trends in oil degradation with time

pollutants (Gu *et al.*, 2012). Likewise, in landfarming, a high temperature of about 40 °C leads to increased degradation (Hesnawi and Mogadami, 2013). At very high temperatures (above 40 °C), many bacterial species experience a decline in vigor as a result of damage to their cellular structures, leading to reduced biodegradation (Stepanova *et al.*, 2022). Temperature has a considerable effect on the ability of the in-situ microorganisms to degrade oil. The solubility of oil increases with temperature, which ultimately increases the bioavailability of the oil molecules (Sihag, et al., 2014).

Moisture

In both photochemical oxidation and landfarming, soil moisture is necessary because it promotes $OH^{\bullet}$ radical production and microbial activity, which significantly impact the method's effectiveness. The ideal moisture range, which permits oxygen to get through for microbial respiration, will allow for a soil moisture level between 20 and 50 percent of its water-holding capacity (Okoh, et al., 2020). All the contaminated soil samples used in this work had moisture content greater than 20% as required (Table 1). If contaminated soil is saturated with water, oxygen will not be able to move through it. The presence of a proper amount of water can facilitate degradation, mostly because water creates favorable conditions for delivering pollutants to the catalyst surface. Because water is required for the production of $OH^{\bullet}$ in photochemical oxidation, the oil removal process increases with rising humidity (Mekkiyah *et al.*, 2023).

pH

The pH of the oil-contaminated soil samples (control samples) collected from MCM before treatment was 4.5. The low pH of the oil-contaminated soil samples may be due to the presence of several free cations in the oil, which gives them the characteristics of a weak acid (Akpoveta *et al.*, 2011). A considerable increase in pH (from 5.5-7.6) was seen in microcosms after treatment (Table 2), suggesting a reduction in the oil content of the soil (Akpoveta *et al.*, 2011).

Total oil reduction analysis

Samples from the experimental and control groups were collected on days 0, 7, 14, 21, 28, and 35 to analyze the total oil content and kinetics of oil deterioration (Mohajeri *et al.*, 2013). The oil concentration at day 0 in the oil-contaminated soil was 56.6 mg/kg as determined by the TOG/TPH infracal method. Fig. 4 shows the trends in the oil reduction in the experimental and control setups. The table shows the amount of oil still present in the soil at a specified time in days.

The oil reduction was more in the biocarb + grafted South Luangwa (80.47%), whereas the least oil reduction was seen in the control (23.91%). The percentage of oil reduction in the control was comparable with the residue in the biocarb. The outcomes of the present investigation are in agreement with the findings of Wu *et al*. (2017) and Sarkar *et al.* (2005). When compared to natural attenuation, the addition of nutrients to the oil-contaminated soil in both studies did not improve the oil removal. In an earlier study by Wang *et al*. (2016), it was found that after 175 days of landfarming with fertilizer addition in the microcosm, a TPH elimination efficiency of just 37% was reached in an aged lubricant and diesel-oil polluted field soil. The nature and concentration of

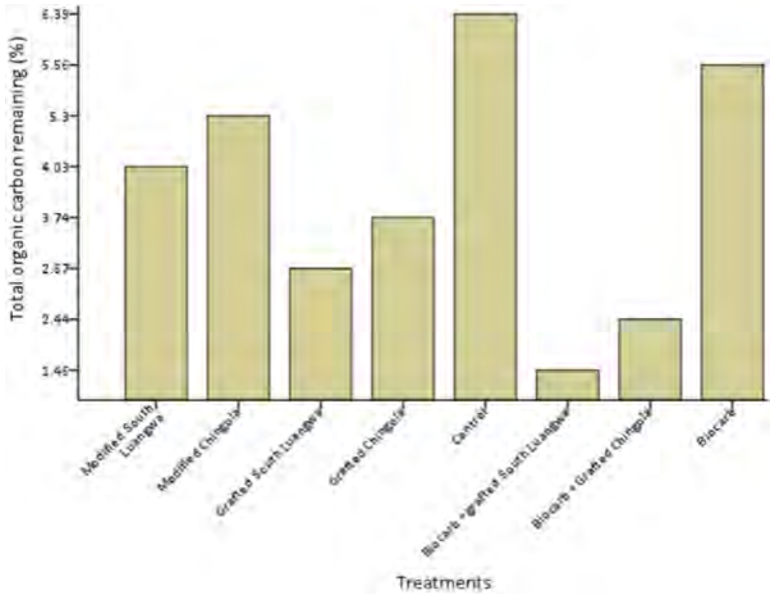

Fig. 5: Relative amount of organic carbon remaining in each soil sample

oil contamination may also be considerably impacted by physical and chemical weathering, which makes it more challenging for natural biodegraders to function. Moreover, the complex mixes of these oils that are meant to be available and accessible may contain substrates that are too large for the native microbial communities to break down (Yuniati, 2018). PAHs are among the components of crude oil that are particularly concerning because they are likely carcinogens and persist in the environment due to being resistant to microbial breakdown (Kang *et al.*, 2020). Poor solubility in soil aqueous solution and the oil absorbed on soil particles may result in poor bioavailability. This retards the biodegradation rate of the oil at the solid–liquid interface of the soil (Zhang *et al.*, 2020). That said, the higher reduction in biocarb + grafted South Luangwa could be attributed to a number of factors including high surface area, the presence of interlayer cations, as well as adsorption, which leads to the accumulation and delivery of the oil pollutants onto the clay surface, enhancing the degradation of the oil (Ugochukwu *et al.*, 2014). The relatively higher ratios of silicon per aluminum (Si/Al) in the current study indicate that the clays have high porosity (Schackow *et al.*, 2020). A high porosity facilitates the easy transit of the pollutants and degradation products inside the porous framework of the clay catalyst. This is because, according to Dlamini *et al.* (2022), TiO_2/clay photocatalysts degrade pollutants by the adsorb-degrade-release kind of mechanism. The higher ratios also provide information on the material's permeability against humidity (Baloyi *et al.*, 2018). Good permeability in the clay may have also led to the higher degradation. Despite Chingola having lower bandgap energy as compared to South Luangwa, implying that it was absorbing more visible light than South Luangwa, its performance in the degradation of oil was still low, perhaps because South Luangwa had more favorable properties such as large surface area and pore volume.

Total organic carbon content analysis

The initial TOC content in the contaminated samples (control) was 35%. This value was used as a parameter to calculate the amount of oil that had been degraded and to choose the most suitable mitigation method from among landfarming, photochemical oxidation, and combined landfarming and photochemical oxidation. Fig. 5 displays the proportion of TOC still present in the soil using the Walkey-Black method (Emoyan *et al.*, 2018). A reduction in the TOC in all the treatments was observed (Fig. 5) with the highest reduction being in the biocarb + grafted south Luangwa (combined landfarming and photochemical oxidation method) with only 1.46% total carbon remaining after treatment, whereas the current landfarming method employed by MCM still had considerable TOC.

The control had the highest amount of total carbon residue (6.39%) under natural attenuation. The grafted South Luangwa/biocarb was better than the grafted Chingola/biocarb because the former had a higher surface area and greater pore volume, which enhanced the photocatalytic properties. The TOC reduction was a result of the reduction in the oil content. A similar trend in the TOC reduction was observed in relation to oil reduction.

Kinetics of photochemical oxidation and landfarming

Kinetics of photochemical oxidation and landfarming characterize the quantity or concentration of pollutant (oil) remaining in the soil at a specific time, making it possible to predict how much oil would still be available at a specific point in the future (Agarry *et al.*, 2013). In the current study, the entire oil content data were fitted into the first-order kinetics (Akpoveta *et al.*, 2011) using the equation $C = Coe^{-kt}$, where C represents the amount of oil contained in the soil milligram per kilogram (mg/kg) at a time t, Co is the initial amount of oil contained in the soil (mg/kg), *k* is the degradation rate constant (/day), whereas t is the time in days and e is the base of natural log. Degradation rates and half-lives that were estimated by this model were compared to the treatment options used by Arjoon and Speight (2020). The degradation half-life ($t_{½}$) = natural logarithm of 2 divided by K ($\frac{\ln 2}{k}$)is the time taken for a substance to lose half of its amount and describes the contaminants' transformation (Agarry *et al.*, 2013; Ofoegbu *et al.*, 2015). Therefore, efficiencies of oil degradation for the treatment systems under study were done through kinetic modeling, which was used to determine the rates of chemical processes (Safdari *et al.*, 2018). The concentrations of the oil left in the soil at regularly spaced intervals and their natural logarithms were plotted against time as shown (Fig. 6) to analyze the degradation processes. The first-order and second-order kinetics were both performed on the data, but the coefficient of determination (R^2) values were higher for first order. The degradation followed first-order kinetics because the plots of the ln of oil concentration against time were linear (Shen *et al.*, 2016; Wang *et al.*, 2016).

The rate constants derived from first-order kinetic modeling in Fig. 6 show how different treatments affect oil breakdown in oil-contaminated soils relative to one another. Table 3 shows how each treatment affected the degradation rate constant (k) and the related degradation half-lives ($t_{½}$). The rate constant, k, was generally between 0.007 and 0.049/days, with 0.007/days being the rate constant for natural attenuation (control). The rate of degradation also increases with greater degradation rate constants, which leads to a decrease in the half-life of degradation (Agarry *et al.*, 2013; Ofoegbu *et al.*, 2015). The variations in the rate constants and half-life times observed in the different treatments may be due to a number of reasons including enhanced adsorption of contaminants and bioavailability in treatments where modified and grafted clay catalysts were combined with biocarb. The half-lives ranged from 15.2-94.8 days. When deciding whether or not to classify a chemical as persistent, the half-life might be utilized as the primary benchmark. Persistent substances exhibit a half-life that is longer than 40 days (Acharya *et al.*, 2019; Mohajeri *et al.*, 2013). Because different components of crude oil such as aliphatic, aromatic, and polycyclic chemicals have varying degradation rates, the prediction of oil degradation kinetics is frequently challenging and complex (Xu *et al.*, 2015). The R^2 values ranged from 0.848-0.93 (Table 3). The low R^2 values obtained could be attributed to variations in temperature during the treatment period, given the study was conducted toward the end of the rainy season. Low R^2 values ranging from 0.69-0.99 have been recorded in the past (Uba *et al*., 2019). Consequently, the R^2 values found in this investigation show that the decline in oil concentrations in the soil as a function of time is linear and positively correlated (Nwankwegu *et al.*, 2016).

The percentage variations in rate constants and half-lives between the different treatments are shown in Table 4. In this study, there was no significant difference in the rate of oil degradation or the amount of time needed for the oil to totally break down between the control and biocarb (p = 0.14).

ANOVA analysis

The ANOVA test revealed that differences in treatment means were not statistically significant with p = 0.14 as shown in Table 5. Multiple comparisons test showed that there was no significant difference between natural attenuation (control) and landfarming (biocarb), which is similar to the findings of Shen *et al.* (2016) where p = 0.912. There was a statistically significant difference between the control and biocarb + grafted South Luangwa (p = 0.029) and biocarb and grafted South Luangwa (p = 0.037). The oil decrease

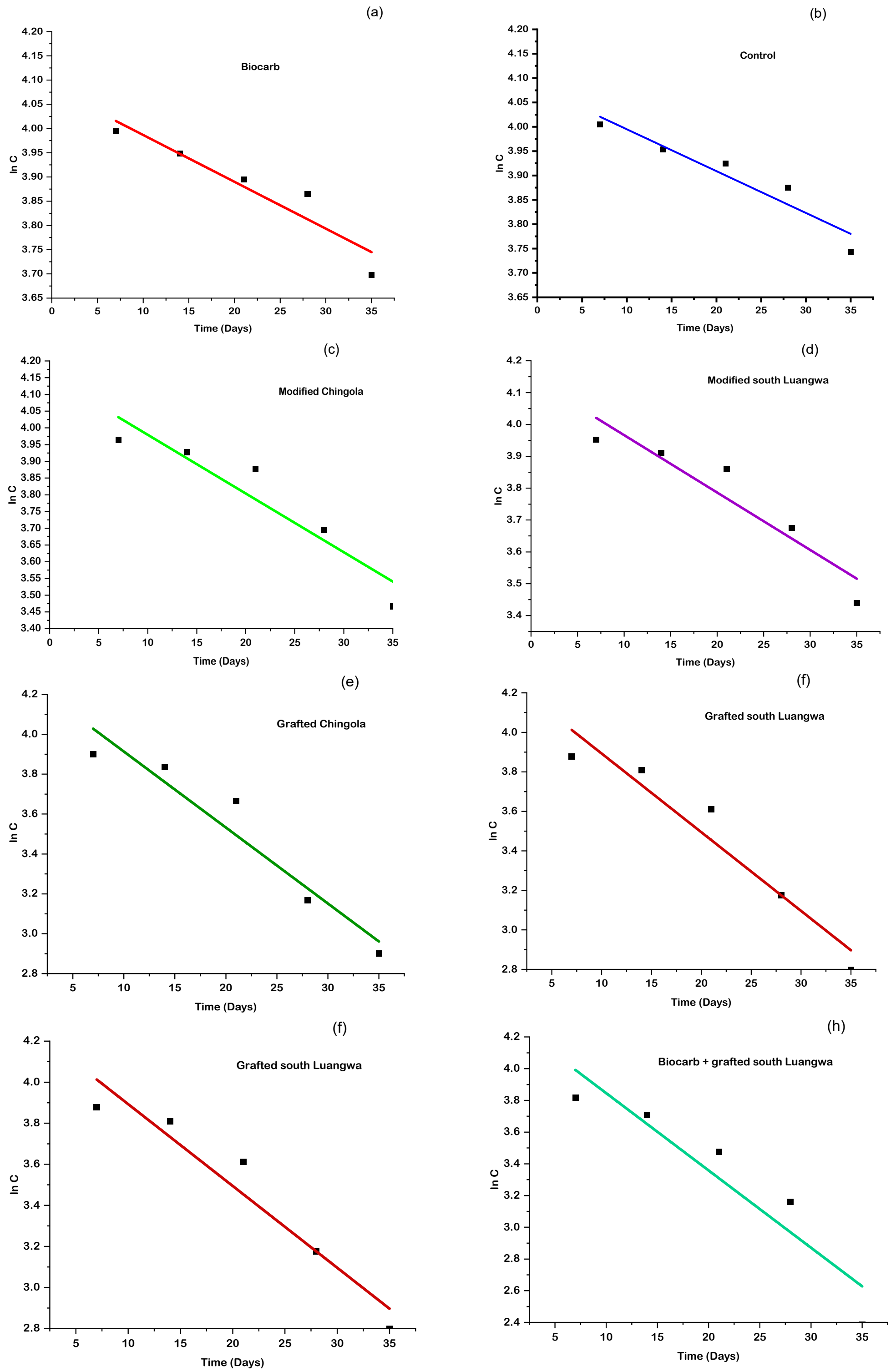

Fig. 6: First-order kinetics model fitted to the degradation data of oil in the soil treatments

Table 3: Relationship between treatment and rate of decay (half-life)

Sample	Control	Biocarb	MC	GC	ML	GL	B&GC	B&GL
Rate constant	0.007	0.008	0.018	0.038	0.015	0.040	0.046	0.049
Half-life (days)	94.802	83.094	44.971	30.130	39.487	18.194	17.395	15.201
R^2	0.871	0.859	0.907	0.924	0.848	0.931	0.894	0.881
P	0.004	0.005	0.006	0.003	0.006	0.003	0.005	0.005

MC (modified Chingola), GC (grafted Chingola), ML (modified South Luangwa), GL (grafted South Luangwa), B&GC (biocarb + grafted Chingola), B&GL (biocarb + grafted South Luangwa).

Table 4: Comparison of rate constants and half-lives for different treatments

Treatment	Difference in k (%)	Difference in $t_{½}$ (%)
Control and biocarb	13	13
Control and MC	72	71.3
Control and ML	88	82.4
Biocarb and MC	60.8	59.5
Biocarb and ML	76.9	71.15
Control and B&GC	78.8	74.79
Control and B&GL	80	77.7
MC and ML	11.76	8.47
Control and GC	74.69	58.86
Control and GL	75.86	73.73
Biocarb and GC	71.43	53.95
Biocarb and GL	66.67	70.39

in the control and biocarb + grafted Chingola was also significant (p = 0.043). The quality of landfarming and photochemical oxidation were assessed from the percentage reduction of oil and TOC in the soil as seen from Figs. 4 and 5. The results are consistent with the study conducted by Fanaei *et al.* (2020). None of the treatments in photochemical oxidation, that is, modified MC, ML, GC, and GL, were significantly different from the control and biocarb treatments.

Oil degradation trends for each treatment are displayed in Fig. 7. The study has demonstrated that combined photochemical oxidation and landfarming (biocarb + GL and biocarb + GC) treatments of oil-contaminated soil can achieve high levels of oil removal, particularly for biocarb + GL, which also had the highest TOC removal as can be seen in Fig. 5 (Liao *et al.*, 2018; Okonofua *et al.*, 2020). The differences in degradation activity of biocarb + GL and biocarb + GC could be likely due to differences in the BET surface or density of $OH^{\bullet}$ present on their surfaces (Haque *et al.*, 2012). For instance, the South Luangwa (bentonite) utilized in this investigation is made up of an octahedral arrangement of AlO_2 between two sheets of SiO_2. Owing to isomorphic substitutions of Mg ions (Mg^{2+}) for aluminum ions (Al^{3+}) in the octahedral layer and Al^{3+} for Si ions (Si^{4+}) in the tetrahedral layer, bentonite has a negative charge. Exchangeable cations (such as sodium ions, potassium ions, and calcium ions [Na^+, K^+, Ca^{2+} respectively]) are present in the interlayer area to counteract this negative charge. These cations make it easy for bentonite to adsorb pollutants, and they can be, naturally or through ionic exchange, exchanged with other metal cations (Bananezhad *et al.*, 2019). These naturally occurring or exchanged cations provide clays, such as bentonite (South Luangwa); their affinity for aromatic hydrocarbons, which make up 17-50 percent weight of crude oil (Speight, 2016); and they also accelerate changes. Additionally, ML has a higher surface area compared to MC (Mambwe *et al.*, 2023). The other reason for the increased degradation rate could have been due to the ability of biocarb to promote microbial activity. The use of biocarb plus GC and GL incorporated adsorption, chemical oxidation, and bioremediation. The combination of adsorption, photochemical oxidation, and bioremediation is known to produce little to no residues and produces

Table 5: ANOVA statistical results

ANOVA					
Oil content	Sum of squares	Df	Mean square	F	Sig.
Between groups	1720.795	7	245.828	1.688	.140
Within groups	5824.173	40	145.604		
Total	7544.968	47			

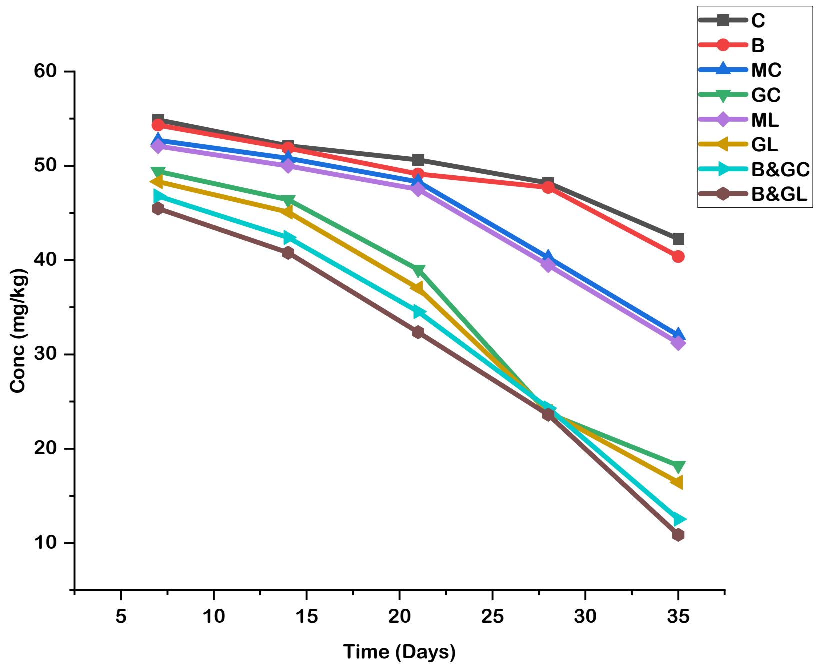

Fig. 7: Concentrations of oil in the various treatments from day 7-35. C (control), MC (modified Chingola), GC (grafted Chingola), ML (modified South Luangwa), GL (grafted South Luangwa), B and GC (biocarb + grafted Chingola), B and GL (biocarb + grafted South Luangwa)

a low carbon footprint, making it a cost-effective way to treat oils in all environmental media (Okoh *et al.*, 2020). Nonetheless, adding biocarb to the soil reduces soil density, thereby increasing porosity and the rate at which oxygen is distributed in the soil (Wang *et al.*, 2019). Photochemical oxidation has been utilized as an additional approach to reduce pollutants to manageable levels and obtain molecules that are readily biodegradable (Yan *et al.*, 2023). Photochemical oxidation can promote bioremediation by increasing contaminated substrate bioavailability and biodegradability, supplying oxygen, and occasionally releasing nutrients (Sutton *et al.*, 2014). This is achieved by accumulation of oil particles on the clay surface, resulting in their immobilization via ion–dipole interactions, coordination, or exchange mechanisms (Srinivasan, 2011). When clays modified with TiO_2/Mn are irradiated with light, e^--hole pairs are created that when in contact with air form $O_2^{\bullet}$ and $OH^{\bullet}$ radicals. These radicals have the ability to nonselectively mineralize a range of adsorbed organic compounds into benign byproducts such as carbon dioxide, water, and inorganic ions, either partially or fully (Gaur *et al.*, 2022). Metal loading on the clay surface further enhances the material's surface area and pore volume (Mishra *et al.*, 2018). This then increases the number of active surface sites. The increased surface area allows for more molecules to interact with the surface, thereby hastening the degradation of oil molecules (Surya *et al.*, 2018). The doping of the clays with Mn leads to structural distortions and changes in the chemical composition. These changes affect the electronic structure and, as a result, alter the optical response by reducing the bandgap (Denison *et al.*,

Table 6: Summary of some remediation techniques for treating soil polluted with oil

Procedure	Focus	Results	Sources
Bioremediation	Wheat bran and swine wastewater were used to remediate the contaminated soil.	A degradation efficiency of 68.27 ± 0.71 percent was attained after 40 days.	Zhang *et al*., 2020
Landfarming	Hydrocarbon-polluted soil was cleaned up using land farming, phytoremediation, and chemical-biological techniques.	Following treatment using the landfarming technique, a degradation of over 90% of the initial levels of the PAH and TPH was observed.	Okonofua *et al*., 2020
Photochemical oxidation	The study coupled landfarming with photochemical oxidation with TiO_2 as a photocatalyst to remediate soil contaminated by crude oil.	The greatest removal efficiencies, of 67% and 59%, were obtained from 0.5% and 2% of TiO_2.	Effendi and Aminati, 2019
Bioremediation	Petroleum-contaminated soil was treated using aged waste from landfills.	Following 98 days of treatment, efficiency increased from 22.40% to 89.83%.	Liu *et al*., 2018
Natural attenuation	Enhancing long-term groundwater contamination at locations where attenuation-based treatments are being used	The physical and chemical mechanisms that cause pollutant attenuation were to be monitored closely as part of the long-term monitoring approach.	Denham *et al*., 2020
Photochemical oxidation	The comparative photodegradation activities of pentachlorophenol (PCP) and polychlorinated biphenyls using UV alone and TiO2-derived photocatalysts in methanol soil washing solution	The percentages of PCP removed after 120 minutes were 94%, 92%, and 57%.	Zhou *et al*., 2014
Bioremediation	The petroleum in the contaminated soil was broken down using sawdust and rice straw.	After 5 months, the TPH removal percentages were 23.9%, 45.2%, and 27.5%, whereas the PAH removal percentages for the sawdust, rice straw, and control treatments were 66.3%, 30.3%, and 26.9%.	Huang *et al*., 2019

2022). Previous research works have shown that nutrition supplementation promotes bioremediation by boosting microbial biomass (Denham *et al.*, 2020). It is also possible that nutrients from biocarb could have boosted the microbial biomass, resulting in increased oil degradation in the treatments with combined photochemical oxidation and landfarming. Photochemical oxidation may increase the degradability of contaminants, generally through the cleavage of large organic compounds into smaller ones (Medina *et al.*, 2018). A study conducted by Zhou *et al.* (2014) showed that the photodegradation rate rises with pH; the mechanism underlying this stimulatory impact is that more $OH^{\bullet}$ may be generated when the soil pH is greater. Numerous remediation studies have revealed that the ideal pH range for accelerated pollutant degradation is often between pH 6.5 and 8.5, with a pH of 7.8 being the most favorable in the majority of soils. Permeability, growth of microorganisms, dissolution of soil metals, and accessibility of nutrients are all influenced by pH (Okoh *et al.*, 2020). This could be another reason for higher degradation rates in the combined treatments. Our findings are similar to results obtained by da Rocha *et al.* (2012). In this study, the modified as well as the grafted clays showed superior oil decomposition compared to biocarb in the remediation of oil-contaminated soil. Enhanced hydrophobicity promotes hydrophobic interaction between clay and the oil molecules, which in turn enhance both adsorption capacity and the photocatalytic degradation efficiency. Increased porosity in GL could have increased permeability, allowing for easy diffusion of nutrients and bacteria (Zhu *et al.*, 2020). Oil biodegraders sourced from oil-polluted sites have shown limited adaptation with low degradation rates owing to the wide oil metabolism pathways (Cui *et al.*, 2023). This could have affected the degradation of oil in the biocarb and the control treatments. Abiotic variables such as sorption and volatilization cause natural attenuation to happen in the control (Uba *et al.*, 2019), yet Franco *et al.* (2014) considered volatilization as a negligibly opposing process. These techniques are usually conducted in simulative environments, but when conducted in the fields where the conditions may not always be ideal, the results might vary. In the current study, experiments were conducted outside, but in most studies, experiments are carried out in simulative environments, and this may have contributed to the variations (Bakina *et al.*, 2021). The degradation of oil in soils is a highly complicated process that depends on a variety of elements such as the nature of oil, degree and length of pollution, and characteristics of the soil itself (Polyak *et al.*, 2020). As such, the exact combination of photochemical oxidation and landfarming to effectively remove oil-contaminated soil cannot be determined.

Similar studies performed indicate that the success of the remediation of oil-contaminated soil and other organic pollutants depends on several factors highted in the discussion. Table 6 shows some of the studies and their findings.

CONCLUSION

The various treatments used in the bioremediation of oil-contaminated soil produced positive results, but with varying degrees of oil breakdown, as well as a decline in the acidic content of the oil in the contaminated soil. Lower percentage degradations could be attributed to short time of treatment (35 days) because heavy oils present in the soil take time to break down. The decrease in the amount of oil, which was estimated by the change in oil in soil before and after remediation, is one of the main indicators determining the effectiveness of treatments. The longest half-life time of 94 days was recorded in the control treatment. This shows that oil in the polluted soil can be degraded naturally, but the process maybe very slow and would be effective over a very long period of time. The shortest half-life time of 15 days was recorded in the combined photochemical oxidation and landfarming (biocarb + GL). Findings from this study suggest that remediation of oil-contaminated soil with biocarb + GL led to quick elimination of oil. Therefore, the combination of photochemical oxidation and landfarming was effective and significantly boosted the degradation and loss of oil in the contaminated soils with high degradation constants and low half-lives. It is also worth noting that mere reliance on bioremediation of the oil contaminants in the soil could take a very long time for significant remediation to be achieved. The minimal oil depletion observed in the control and biocarb soil justifies this view. The combined remediation techniques used in this study offer a promising, better, cheaper, and more eco-friendly approach that, if adequately applied in oil-polluted soil, will lead to a harmless and nontoxic environment for both plant and animal well-being. The findings also suggest that the effective breakdown of oil and reduction of the remediation period might be achieved using photochemical oxidation with clay materials. Treatment of soil with photochemical oxidation is predicted to increase the oil bioavailability and the rate at which it is degraded in the soil. Photochemical oxidation was found to be a better remediation technique of oil-contaminated soil compared to the landfarming method. There is a need for MCM to consider adopting photochemical oxidation as a remediation technique in its treatment of oil-contaminated soil within the vicinity of its mines. Although photochemical oxidation can thoroughly remedy oil-contaminated soil with great efficacy, research on the nature of the intermediate compounds produced during remediation is scarce. More research on the subject matter is required to understand how these substances impact the environment.

AUTHOR CONTRIBUTIONS

K. K. Kalebaila, the corresponding author, has contributed in supervising. M. Mambwe assisted in the data analysis, interpreting the results, and preparing the manuscript. M. Mambwe prepared all the tables and figures and interpretation of the results. T. Johnson participated in the supervision, interpretation of the results, and manuscript preparation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
%R	Percentage of oil degradation after treatment
°C	Degree Celsius
Al	Aluminum
Al^{3+}	Aluminum ion
Al_2O_3	Aluminum oxide
ANOVA	Analysis of variance
B	Biocarb
B&GC	Biocarb + grafted Chingola
B&GL	Biocarb + grafted South Luangwa
BET	Brunauer Emmett Teller
BJH	Barret-Joyner-Halenda
C	Control
Ca^{2+}	Calcium ion
Ce	Concentration of oil at time, t
Conc.	Concentration
Co	Initial concentration of oil (time is zero)
cm^3/g	Cubic centimeters per gram
/day	Per day
E	Base of natural log
Eq	Equation
eV	Electron volt
FTIR	Fourier transform infrared
G	Gram
GC	Grafted Chingola
GL	Grafted South Luangwa
ICP	Inductively coupled plasma
K^+	Potassium ion
K	Rate constant
Kg	Kilogram
Ln	Natural logarithm
lnC	Natural logarithm of concentration
LSD	Fisher's least significant difference
M	Molar
MC	Modified Chingola
MCM	Mopani Copper Mines
Mg^{2+}	Magnesium ion
m^2/g	Square meters per gram
mg/Kg	Milligrams per kilogram
Min	Minutes
ML	Modified South Luangwa
Ml	Milliliter
Mm	Millimeter
Mn	Manganese

$Mn(NO_3)_2$	Manganese (II) nitrate
Na^+	Sodium ion
Nm	Nanometer
$OH^•$	Hydroxyl radical
P	A statistical measurement used to validate a hypothesis against observed data
PAHs	Polyaromatic hydrocarbons
pH	Potential of hydrogen
R^2	Coefficient of determination
Si	Silicon
Si^{4+}	Silicon ion
SiO_2	Silicon dioxide
SPSS	Statistical Package for Social Sciences
t	Time
TOC	Total organic carbon
TOG	Total oil grease
TPH	Total petroleum hydrocarbons
TiO_2/Mn	Titanium dioxide per manganese
$Ti(OPr_4)$	Titanium isopropoxide
USEPA	United States Environmental Protection Agency
UC	Unmodified Chingola
UL	Unmodified South Luangwa
UV-Vis	Ultraviolet-visible spectroscopy
v:v	Volume per volume
XRF	X-ray fluorescence

REFERENCES

Abioye, O.P.; Agamuthu, P.; Abdul Aziz, A.R., (2011). Phytotreatment of soil contaminated with used lubricating oil using Hibiscus cannabinus. Biodegradation. 23 (2): 277–286 **(10 pages).**

Acharya, K.; Werner, D.; Dolfing, J.; Barycki, M.; Meynet, P.; Mrozik, W.; Komolafe, O.; Puzyn, T.; Davenport, R. J., (2019). A quantitative structure-biodegradation relationship (QSBR) approach to predict biodegradation rates of aromatic chemicals. Water Res., 157: 181-190 **(10 pages).**

Agarry, S.E.; Aremu, M.O.; Aworanti, O.A., (2013). Kinetic modelling and half-life study on enhanced soil bioremediation of bonny light crude oil amended with crop and animal-derived organic wastes. J. Pet. Environ. Biotechnol., 4(2): 137-147 **(11 pages).**

Aichner, B.; Bussian, B.; Lehnik-Habrink, P.; Hein, S., (2013). Levels and spatial distribution of persistent organic pollutants in the environment: a case study of German forest soils. Environ. Sci. technol., 47(22): 12703-12714 **(12 pages).**

Akinwumiju, A.S.; Adelodun, A.A.; Ogundeji, S.E., (2020). Geospatial assessment of oil spill pollution in the Niger Delta of Nigeria: an evidence-based evaluation of causes and potential remedies. Environ. Pollut., 267: 115545 **(13 pages).**

Akpoveta, O.V.; Egharevba, F.; Medjor, O.W.; Osaro, K.I.; Enyemike, E.D., (2011). Microbial degradation and its kinetics on crude oil polluted soil. Res. J. Chemi. Sci., 1 (16): 8-14 **(7 pages).**

Almutairi, M.S., (2022). Determination of total petroleum hydrocarbons (TPHs) in weathered oil contaminated soil. Environ. Eng. Res., 27(5): 210324 **(7 pages).**

Arjoon, K.; Speight, J.G., (2020). Chemical and physical analysis of a petroleum hydrocarbon contamination on a soil sample to determine its natural degradation feasibility. Inventions. 5(3): 43 **(10 pages).**

Bakina, L.G.; Chugunova, M.V.; Polyak, Y.M.; Mayachkina, N.V.; Gerasimov, A.O., (2021). Bioaugmentation: possible scenarios due to application of bacterial preparations for remediation of oil-contaminated soil. Environ. Geochem. Health. 43(6): 2347-2356 **(10 pages).**

Baloyi, J.; Ntho; Moma, J., (2018). A novel synthesis method of Al/Cr pillared clay and its applicatio application in the catalytic wet air oxidation of phenol. Catal. Lett., 148: 3655- 3668 **(14 pages).**

Bananezhad, B.; Islami, M.R.; Ghonchepour, E.; Mostafavi, H.; Tikdari, A.M.; Rafiei, H.R., (2019). Bentonite clay as an efficient substrate for the synthesis of the super stable and recoverable magnetic nanocomposite of palladium (Fe_3O_4/Bentonite-Pd). Polyhedron, 162: 192-200 **(9 pages).**

Brame, J.A.; Hong, S.W.; Lee, J.; Lee. SH.; Alvarez, P.J.J., (2013). Photocatalytic pretreatment with food grade TiO_2 increases the bioavailability and bioremediation potential of weathered oil from the deepwater horizon oil spill in the Gulf of Mexico. Chemosphere. 90(8): 2315-2319 **(5 pages).**

Brown, D.M.; Bonte, M.; Gill, R.; Dawick, J.; Boogaard, P.J., (2017). Heavy hydrocarbon fate and transport in the environment. Q. J. Eng. Geol. Hydrogeol., 50: 333–346 **(14 pages).**

Cui, J.Q.; He, Z. Q.; Ntakirutimana, S.; Liu, Z.H.; Li, B.Z.; Yuan, Y.J., (2023). Artificial mixed microbial system for polycyclic aromatic hydrocarbons degradation. Front. Microbiol., 14 (1207196): **(12 pages).**

da Rocha, O.R.S.; Dantas, R.F.; Duarte, M.M.B.; Duarte, M.M.L.; da Silva, V. L., (2012). Remediation of petroleum contaminated soil by photo-Fenton process applying black, white and germicidal light. Afinidad. 69 (557): 42-46 **(5 pages).**

Denham, M.E.; Amidon, M.B.; Wainwright, M.; Dafflon, B.; Ajo-Franklin, J.; Eddy-Dilek, C.A., (2020). Improving long-term monitoring of contaminated groundwater at sites where attenuation based remedies are deployed. Environ. Manage., 66: 1142-1161 **(20 pages).**

Denison, S.B.; Da Silva, P.D.; Koester, C.P.; Alvarez, P.J.; Zygourakis, K., (2022). Clays play a catalytic role in pyrolytic treatment of crude-oil contaminated soils that is enhanced by ion-exchanged transition metals. J. Hazard. Mater., 437: 129295 **(9 pages).**

Dlamini, M.C.; Dlamini, M.L. Mente, P.; Tlhaole, B.; Erasmus, R.; Maubane-Nkadimeng, M.S.; Moma, J.A., (2022). Photocatalytic abatement of phenol on amorphous TiO_2-BiOBr-bentonite heterostructures under visible light irradiation. J. Ind. Eng. Chem., 111: 419-436 **(18 pages).**

Dzionek, A.; Wojcieszyńska, D.; Guzik, U., (2016). Natural carriers in bioremediation: a review. Electron. J. Biotechnol., 23: 28–36 **(9 pages).**

Effendi, A.J.; Aminati, T., (2019). Enhancing bioremediation of crude oil contaminated soil by combining with photocatalytic process using TiO_2 as catalyst. Geomate J., 17 (64): 100-107 **(8 pages).**

Emoyan, O.O.; Akporido, S.O.; Agbaire, P.O., (2018). Effects of soil pH, total organic carbon and texture on fate of polycyclic aromatic hydrocarbons (PAHs) in soils. Global NEST J., 20(2): 181-187 **(7 pages).**

Fanaei, F.; Moussavi, G.; Shekoohiyan, G., (2020). Enhanced treatment of the oil-contaminated soil using biosurfactant-assisted washing operation combined with H_2O_2-stimulated biotreatment of the effluent. J. Environ. Manage., 271: 110941 **(8 pages).**

Farooq, S.; ASiddiqa, A.; Ashraf, S.; Haider, S.; Imran, S.; Shahida, S.; Qaisar, S., (2022). Effective removal of arsenic (V) from aqueous solutions using efficient CuO/TiO_2 nanocomposite adsorbent. Eur. J. Chem., 13 (3): 284-292 **(9 pages).**

Franco, M.G.; Corrêa, S.M.; Marques, M., Perez, D.V., (2014). Emission of volatile organic compounds and greenhouse gases from the anaerobic bioremediation of soils contaminated with diesel. Water Air Soil Pollut., 225: 1-9 (**9 pages).**

Gaur, N.; Dutta, D.; Singh, A.; Dubey, R.; Kamboj, D.V., (2022). Recent advances in the elimination of persistent organic pollutants by photocatalysis. Front. Environ. Sci., 10, 872514 **(29 pages).**

Gu, J.; Dong, D.; Kong, L.; Zheng, Y.; Li, X., (2012). Photocatalytic degradation of phenanthrene on soil surfaces in the presence of nanometer anatase TiO_2 under UV-light. J. Environ. Sci., 24 (12): 2122-2126 **(5 pages).**

Hadei, M.; Mesdaghinia, A.; Nabizadeh, R.; Mahvi, A.H.; Rabbani, S.; Naddafi, K., (2021). A comprehensive systematic review of photocatalytic degradation of pesticides using nano TiO_2. Environ. Sci. Pollut. Res., 28: 13055-13071 **(18 pages).**

Hadnadjev-Kostic, M.; Vulic, T.; Marinkovic-Neducin, R., (2014). Solar light induced rhodamine B degradation assisted by TiO_2-Zn-Al LDH based photocatalys. Adv. Powder Technol., 25(5): 1624-1633 **(10 pages).**

Haque, M.M.; Detlef, B.; Mohammad, M., (2012). Photocatalytic degradation of organic pollutants: Mechanisms and kinetics. Organic pollutants ten years after the Stockholm Convention–Environmental and analytical update. London, UK: IntechOpen **(33 pages).**

He, X.; de la Cruz, A.A.; O'Shea, K.E.; Dionysiou, D.D., (2014). Kinetics and mechanisms of cylindrospermopsin destruction by sulfate radical-based advanced oxidation processes. Water Res., 63: 168-178 **(11 pages).**

Hesnawi, R.M.; Mogadami, F.S., (2013). Bioremediation of Libyan crude oil-contaminated soil under mesophilic and thermophilic conditions. Apcbee Procedia. 5: 82-87 **(6 pages).**

Huang, Y.; Pan, H.; Wang, Q.; Ge, Y.; Liu, W.; Christie, P., (2019). Enrichment of soil microbial community in the bioremediation of a petroleum contaminated soil amended with rice straw or sawdust. Chemosphere. 224:265-271 **(7 pages).**

Hussain, M.; Akhter, P.; Iqbal, J.; Ali, Z.; Yang, W.; Shehzad, N.; Russo, N., (2017). VOCs photocatalytic abatement using nanostructured titania-silica catalysts. J. Environ. Chem. Eng., 5(4): 3100-3107 **(8 pages).**

Idowu, O.; Semple, K.T.; Ramadass, T.; O'Connor, W.; Hansbro, P.; Thavamani, P., (2019). Beyond the obvious: environmental health implications of polar polycyclic aromatic hydrocarbons. Environ. Int., 123: 543–557 **(15 pages).**

Imam, A., Suman, S.K., Ghosh, D.; Kanaujia, P.K., (2019). Analytical approaches used in monitoring the bioremediation of hydrocarbons in petroleum-contaminated soil and sludge. Trends Anal. Chem., 118: 50-64 **(15 pages).**

Jha, P.; Biswas, A.K.; Lakaria, B.L.; Saha, R.; Singh, M.; Rao, A.S., (2014). Predicting total organic carbon content of soils from Walkley and Black analysis. Commun. Soil Sci. Plant Anal., 45 (6): 713-725 **(23 pages).**

Kang, C.U.; Kim, D.H.; Khan, M.A.; Kumar, R.; Ji, S.E.; Choi, K.W.; Paeng, K.J.; Park, S.; Jeon, B.H., (2020). Pyrolytic remediation of crude oil-contaminated soil. Sci. Total Environ., 713: 1–8 **(8 pages).**

Kebede, G.; Tafese, T.; Abda, E.M.; Kamaraj, M.; Assefa, F., (2021). Factors influencing the bacterial bioremediation of hydrocarbon contaminants in the soil: mechanisms and impacts. J. Chem., 2021: 1-17 **(17 pages).**

Khudur, L.S.; Shahsavari, E.; Miranda, A.F.; Morrison, P.D.; Nugegoda, D.; Ball, A.S., (2015). Evaluating the efficacy of bioremediating a diesel-contaminated soil using ecotoxicological and bacterial community indices. Environ. Sci. Pollut. Res., 22: 14809–14819 **(11 pages).**

Kong, F.X.; Sun, G.D.; Liu, Z.P., (2018). Degradation of polyaromatic hydrocarbons in soil mesocosms by microbial/plant bioaugumentation: performance and mechanism. Chemosphere. 198: 83-91 **(9 pages).**

Liao, X.Y.; Wu, Z.; Li, Y.; Luo, J.; Su, C., (2018). Enhanced degradation of polycyclic aromatic hydrocarbons by indigenous microbes combined with chemical oxidation. Chemosphere. 213: 551–558 **(8 pages).**

Lin, M.S.; Huang, C.Y.; Lin, Y.C.; Lin, S.L.; Hsiao, Y.H.; Tu, P.C.; Cheng, P.C.; Cheng, S.F., (2022). Green remediation technology for total petroleum hydrocarbon-contaminated soil. Agronomy. 12(11): 2759 **(12 pages).**

Liu, J.; Zhang, G., (2014). Recent advances in synthesis and applications of clay- based photocatalysts: A review. Phys. Chem. Phys., 16(18): 8178-8192 **(15 pages).**

Liu, Q.; Li, Q.; Wang, N.; Liu, D.; Zan, L.; Chang, L.; Gou, X.; Wang, P., (2018). Bioremediation of Petroleum contaminated soil using aged refuse from landfills. Waste Manage., 77: 576-585 **(10 pages).**

Mambwe, M.; Kalebaila, K.K.; Johnson, T.; Moma, J., (2023). Modification and characterization of selected Zambian clays for potential use as photocatalysts. Eur. J. Chem., 14 (3): 362-369 **(8 pages).**

Medina, R.; David Gara, P.M.; Fern andez-Gonzalez, A.J.; Rosso, J.A.; Del Panno, M.T., (2018). Remediation of a soil chronically contaminated with hydrocarbons through persulfate oxidation and bioremediation. Sci. Total Environ., 618: 518–530 **(13 pages).**

Mekkiyah, H.M.; Al-Hamadani, Y.A.J.; Abdulhameed, A.A.; Resheq, A.S.; Mohammed, Z.B., (2023). Effect of crude oil on the geotechnical properties of various soils and the developed remediation methods. Appl. Sci., 13: 9103 **(16 pages).**

Michael-Igolima, U.; Abbey, S.J.; Ifelebuegu, A.O., (2022). A systematic review on the effectiveness of remediation methods for oil. Environ. Adva., 9: 100319 **(21 pages).**

Mishra, A.; Mehta, A.; Basu, S., (2018). Clay supported TiO_2 nanoparticles for photocatalytic degradation of environmental pollutants: A review. J. Environ. Chem. Eng., 6(5): 6088-6107 **(25 pages).**

Mohajeri, L.; Aziz, A.H.; Isa, M.H.; Zahed, M.A., (2013). Effect of remediation strategy on crude oil biodegradation kinetics and half-life times in shoreline sediment samples. Int. J. Mar. Sci. Eng., 3 (2): 99-104 **(5 pages).**

Naeem, U.; Qazi, M.A., (2020). Leading edges in bioremediation technologies for removal of petroleum hydrocarbons. Environ. Sci. Pollut. Res., 27(22): 27370-27382 **(13 pages).**

Nwankwegu, A.S.; Onwosi, C.O.; Orji, M. U.; Anaukwu, C.G.; Okafor, U.C.; Azi, F.; Martins, P.E., (2016). Reclamation of DPK hydrocarbon polluted agricultural soil using a selected bulking agent. J. Environ. Manage., 172, 136-142 **(7 pages).**

Ofoegbu, R.U.; Momoh, Y.O.; Nwaogazie, I.L., (2015). Bioremediation of crude oil contaminated soil using organic and inorganic fertilizers. J. Pet. Environ. Biotechnol., 6(1): 1 **(6 pages).**

Okoh, E.; Yelebe, Z.R.; Oruabena, B.; Nelson, E.S.; Indiamaowei, O.P., (2020). Clean up of crude oil contaminated soils: bioremediation option. Int. J. Environ. Sci. Technol. 17(2): 1185-1198 **(14 pages).**

Okonofua, E.S.; Babatola, O.J.; Ojuri, O.; Lasis, K.H., (2020). Determination of suitable TPH remediation approach via MANOVA and inferential statistics assessment. Remediation. 30 (3): 75-87 **(13 pages).**

Polyak, Y.; Bakina, L.; Mayachkina, N.; Polyak, M., (2020). The possible role of toxigenic fungi in ecotoxicity of two contrasting oil-contaminated soils—A field study. Ecotoxicol. Environ. Saf., 202:110959 **(10 pages).**

Safdari, M.S.; Kariminia, H.R.; Rahmati, M.; Fazlollahi, F.; Polasko, A.; Mahendra, S.; Wilding, V., Fletcher, T.H., (2018). Development of bioreactors for comparative study of natural attenuation, biostimulation, and bioaugmentation of petroleum-hydrocarbon. contaminated soil. J. Hazard. Mater., 342: 270-278 **(9 pages).**

Sakshi, S.S.K.; Haritash, A.K., (2019). Polycyclic aromatic hydrocarbons: soil pollution and remediation. Int. J. Environ. Sci. Technol., 16: 6489-6512 **(23 pages).**

Sanie Jahromi, M.S.; Jahromi, S.; Sahraei, R.; Shafa, S.; Ghaedi, M.; Ranjbar, M.; Zabetiana, H., (2023) Comparison of Effects of Oral Melatonin and Gabapentin on Pain and Hemodynamic Symptoms in Patients Undergoing Upper Limb Orthopedic Surgery. Eurasian J. Sci. Tech., 3(4): 165-173 **(9 pages).**

Samimi, M.; Shahriari Moghadam, M., (2020). Phenol biodegradation by bacterial strain O-CH1 isolated from seashore. Global J. Environ. Sci. Manage., 6(1): 109-118 **(10 pages).**

Samimi, M.; Shahriari-Moghadam, M., (2021). Isolation and identification of Delftia lacustris Strain-MS3 as a novel and efficient adsorbent for lead biosorption: Kinetics and thermodynamic studies, optimization of operating variables. Biochem. Eng. J., 173: 108091 **(9 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 (**7 pages).**

Samimi, M.; Safari, M., (2022). TMU-24 (Zn-based MOF) as an advance and recyclable adsorbent for the efficient removal of eosin B: Characterization, equilibrium, and thermodynamic studies. Environ. Prog. Sustain. Energy, 41(5): e13859 **(9 pages).**

Saneha, S.; Pattamapitoon, T.; Bualert, S.; Phewnil, O.; Wararam, W.; Semvimol, N.; Chunkao, K.; Tudsanaton, C.; Srichomphu, M.; Nachaiboon, U.; Wongsrikaew, O.; Wichittrakarn, P.; Chanthasoon, C., (2023). Relationship between bacteria and nitrogen dynamics in wastewater treatment oxidation ponds Global J. Environ. Sci. Manage., 9(4): 707-718 **(12 pages).**

Sarkar, D.; Ferguson, M.; Datta, R.; Birnbaum, S., (2005). Bioremediation of petroleum hydrocarbons in contaminated soils: comparison of biosolids addition, carbon supplementation, and monitored natural attenuation. Environ. Pollut., 136(1): 187-195 **(9 pages).**

Schackow, A.; Correia, S.L.; Effting, C., (2020). Influence of microstructural and morphological properties of raw natural clays on the reactivity of clay brick wastes in a cementitious blend matrix. Cerâmica, 66: 154-163 **(10 pages).**

Shaker, Z.; Almukhtar, E., (2016). Bioaccumulation of petroleum hydrocarbons by Melanopsis nodosa (Gastropoda) in river Tigris within the city of Baghdad. Iraq. Int. J. Curr. Microbiol. Appl. Sci., 5 (1): 244–251 **(8 pages).**

Sharifi, S., (2022) Oil Reservoirs and Exploitation of Oil Reservoirs. Eurasian J. Sci. Tech., 2(2): 161-175 **(15 pages).**

Shen, W.; Zhu, N.; Cui, J.; Wang, H.; Dang, Z.; Wu, P.; Luo, Y.; Shi, C., (2016). Ecotoxicity monitoring and bioindicator screening of oil-contaminated soil during bioremediation. Ecotoxicol. Environ. Saf., 124: 120-128 **(8 pages).**

Sihag, S.; Pathak, H.; Jaroli, D.P., (2014). Factors Affecting the Rate of Biodegradation of Polyaromatic Hydrocarbons. Int. J. Pure Appl. Biosci., 2 (3): 185-202 **(18 pages).**

Silva-Castro, G.A.; Rodelas, B.; Perucha, C.; Laguna, J.; González-López, J.; Calvo, C., (2013). Bioremediation of diesel-polluted soil using biostimulation as post-treatment after oxidation with Fenton-like reagents: assays in a pilot plant. Sci. Total Environ., 445: 347-355 **(9 pages).**

Soliman, R.M.; Sh El-Gendy, N.; Deriase, S.F.; Farahat, L.A.; Mohamed, A.S., (2014). The evaluation of different bioremediation processes for Egyptian oily sludge polluted soil on a microcosm level. Energy Source. Part A., 36 (3): 231-241 **(11 pages).**

Speight, J.G., (2016). Handbook of petroleum refining. CRC press. 1st Edition. Boca Raton, USA, **(789 pages)**.

Srinivasan, R., (2011). Advances in application of natural clay and its composites in removal of biological, organic, and inorganic contaminants from drinking water. Adv. Mater. Sci. Eng., 2011: Article ID 872531 **(17 pages).**

Stepanova, A.Y.; Gladkov, E.A.; Osipova, E.S.; Gladkova, O.V.; Tereshonok, D.V., (2022). Bioremediation of soil from petroleum contamination. Processes. 10 (6): 1224 **(17 pages).**

Surya, L.; Sheilatina, P.V.P.; Sepia, N.S., (2018). Preparation and characterization of titania/bentonite composite application on the degradation of naphthol blue-black dye. Res. J. Chem. Environ., 22(2): 48-53 **(6 pages).**

Sutton, N.B.; Grotenhuis, T.; Rijnaarts, H.H., (2014). Impact of organic carbon and nutrients mobilized during chemical oxidation on subsequent bioremediation of a diesel-contaminated soil. Chemosphere, 97: 64-70 **(7 pages).**

Sutton, N.B; Maphosa, F.; Morillo, J., (2013). Impact of long-term diesel contamination on soil microbial community structure. Appl. Environ. Microbiol., 79 (2): 619–630 **(12 pages).**

Thacharodi, A.; Hassan, S.; Singh, T.; Mandal, R.; Khan, H.A.; Hussain, M.A.; Pugazhendhi, A., (2023). Bioremediation of polycyclic aromatic hydrocarbons: An updated microbiological review. Chemosphere, 328:138498 **(20 pages).**

Uba, B.; Obidinma, M.; Chiamaka, A.; Obioma, C.O.; Chinazo, J.U., (2019). Kinetics of biodegradation of total petroleum hydrocarbon in diesel contaminated soil as mediated by organic and inorganic nutrients. Anim. Res. Int., 16 (2): 3295 – 3307 **(13 pages).**

Ugochukwu, U.C.; Manning, D.A.; Fialips, C.I., (2014). Microbial degradation of crude oil hydrocarbons on organoclay minerals. J.

Environ. Manage., 144: 197-202 **(6 pages).**

Wang, S.Y.; Kuo, Y.C.; Hong, A.; Chang, Y.M.; Kao, C.M., (2016). Bioremediation of diesel and lubricant oil-contaminated soils using enhanced landfarming system. Chemosphere, 164: 558-567 **(10 pages).**

Wang, C.C.; Li, J.R.; Lv, X.L.; Zhang, Y.Q.; Guo, G., (2014). Photocatalytic organic pollutants degradation in metal–organic frameworks. Energy Environ. Sci., 7: 2831-2867 **(37 pages)**.

Wang, X.; Zheng, J.; Han, Z.; Chen, H., (2019). Bioremediation of crude oil-contaminated soil by hydrocarbon-degrading microorganisms immobilized on humic acid-modified biofuel ash. J. Chem. Technol. Biotechnol., 94 (6): 1904-1912 **(9 pages).**

Wu, M.; Ye, X.; Chen, K.; Li, W.; Yuan, J.; Jiang, X., (2017). Bacterial community shift and hydrocarbon transformation during bioremediation of short-term petroleum-contaminated soil. Environ. Pollut., 223: 657-664 **(9 pages).**

Xu, P.; Ma, W.; Han, H.; Jia, S.; Hou, B., (2015). Quantitative structure–biodegradability relationship for biokinetic parameter of polycyclic aromatic hydrocarbons. J. Environ. Sci., 30: 180-185 **(6 pages).**

Yan, X.; An, J.; Zhang, Y.; Wei, S.; He, W.; Zhou, Q., (2023). Photochemical degradation in natural attenuation of characteristics of petroleum hydrocarbons (C10-C40) in crude oil polluted soil by simulated long-term solar irradiation. J. Hazard. Mater., 460: 132259 **(10 pages).**

Yang, Y.; Javed, H.; Zhang, D.; Li, D.; Kamath, R.; McVey, K.; Alvarez, P.J., (2017). Merits and limitations of TiO_2-based photocatalytic pretreatment of soils impacted by crude oil for expediting bioremediation. Front. Chem. Sci. Eng., 11: 387-394 **(8 pages).**

Yuniati, M.D., (2018). Bioremediation of petroleum-contaminated soil: A Review. IOP conf. Series: Earth Environ. Sci., 118: 012063 **(8 pages).**

Zhang, C.; Wu, D.; Ren, H., (2020). Bioremediation of oil contaminated soil using agricultural wastes via microbial consortium. Sci. Rep., 10(1): 9188 **(8 pages).**

Zhou, Z.; Zhang, Y.; Wang, H.; Chen, T.; Lu, W., (2014). The comparative photodegradation activities of pentachlorophenol (PCP) and polychlorinated biphenyls (PCBs) using UV alone and TiO_2-derived photocatalysts in methanol soil washing solution. PLoS One, 9(9): e108765 **(8 pages).**

Zhu, P.; Ren, Z.; Wang, R.; Duan, M.; Xie, L.; Xu, J.; Tian, Y., (2020). Preparation and visible photocatalytic dye degradation of Mn-TiO_2/sepiolite photocatalysts. Front. Mater. Sci., 14: 33-42 **(10 pages).**

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CASE STUDY

Sustainability index analysis for environmentally low-input integrated farming

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ABSTRACT

BACKGROUND AND OBJECTIVES: Integrated farming is an efficient and environmentally friendly agricultural activity that uses low-input resources, including abundant local materials, such as waste. According to previous studies, this program has been adopted by the Indonesian government to facilitate the achievement of sustainable agriculture. Therefore, this study aimed to evaluate the level of sustainability of low-input integrated agricultural farming by determining and analyzing the sustainability index.

METHODS: Experts and business operators engaged in the integrated production of organic fertilizer, corn, and laying hen farming conducted scientific assessments to gather primary and secondary data. This was carried out through Focus Group Discussions and the completion of a questionnaire containing 34 attributes linked to environmental, economical, social, technological, and institutional aspects. The data obtained were then analyzed using a multidimensional scale technique. Monte Carlo analysis and alternating least-squares algorithm were used to examine sustainability status and significant characteristics.

FINDINGS: The degree of agricultural integration's sustainability from organic fertilizer, corn, and layer hen farming was 86.10 percent. The results showed that techniques in several stages of the organic fertilizer production process, corn cultivation with the application of organic fertilizer, and laying hen farming with local feed, harvesting, and marketing, contributed to sustainable development by considering the strength aspects from each dimension. Based on the analysis results, the social dimension had a sustainable index score of 93.79 percent, followed by economic (90.57 percent), institutional (88.39 percent), environmental (83.45 percent), and technology (74.29 percent). Based on the findings, the factors that should be considered included 1) Efficiency in the utilization of water during egg, 2) fertilizer production and effectiveness of using fuel and electricity during the production and marketing, 3) an Industry manager level of education, 4) the ease by which raw materials can be obtained for the integration industry, 5) potential for increasing the low-input integrated agricultural farming, 6) the availability of integration industry facilities, infrastructure and level of expertise needed by managers in the people's integration sector, 7) Financial institutions' existence.

CONCLUSION: Multidimensional mapping showed that the low-input integrated agricultural farming in the dry land of Pangkalan Lada District was running sustainably, with an average sustainability index of 86.10 percent. These results indicated that the integration of organic fertilizer, corn, and layer hen farming in the area had successfully optimized the available resources, created a sustainable farming model, and had the potential for adoption in various locations and future periods. The five evaluated dimensions showed good sustainability levels, with sustainability indices ranging from 74.29 percent (sustainable with a fair level) to 93.79 percent (very sustainable). Therefore, sustainability improvements in these farming activities must focus on technological aspects, with an emphasis on technological attributes that offered valuable insights for the government in formulating policies and programs.

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INTRODUCTION

The Indonesia National Medium-Term Development Plan (RPJMN) for 2020-2024 represents the fourth stage and continuation of the Indonesia National Long-Term Development Plan (RPJPN) for 2005-2025. In the fourth RPJMN (2020-2024), the development of the agricultural sector is expected to enhance food security and competitiveness, leading to the actualization of an advanced, self-reliant, and modern agriculture sector within the country (Ministry of Agriculture, 2021). Several studies have shown that sustainable food security is related to production and closely linked to the engagement and empowerment of farmers who play a frontline role in creating food supplies. Food security is also associated with the management of natural resources. Furthermore, unsustainable exploitation of resources can lead to environmental degradation, soil damage, and negative impacts on agricultural productivity, leading to a decline in the quality and quantity of food production. These challenges can be attributed to the lack of education and training for agricultural practitioners, specifically farmers. According to previous studies, rural farmers do not have adequate access to the latest information and technology for the improvement of production. The lack of access to information, educational opportunities, and training impedes the implementation of Precision Agriculture concepts, such as the use of sustainable fertilizers and pesticides, as well as innovative practices in land management. Precision Agriculture approaches can increase productivity while reducing negative environmental impacts. The low-input integration of agricultural farming or synergy between agriculture and livestock has become a part of the government's programs aimed at providing a solution for sustainable development. Integrated farming systems comprise multiple enterprises or efforts that interact in space and/or time, leading to a synergistic resource transfer among enterprises (Archer *et al.,* 2019). The concept is also described as an agricultural system that uses the three interacting dimensions, namely organization, space, and time (Bell and Moore, 2012). In several developing countries, an integrated farming system is a common practice due to the limitation of farmland acreage, and access to manufactured fertilizers and agrochemicals (Archer *et al*., 2019). At present, the implementation of modern agriculture to enhance production requires intensive inputs. Crop rotation systems and polyculture plants can reduce the intensive input while increasing crop yield, enhancing nutrient cycling, reducing plant disease, and improving soil quality (Hendrikson, 2008). Therefore, the integrated farming system has a potential benefit to environmental aspects and sustainability. For example, its implementation between livestock and cropping systems often enhances nutrient cycling efficiency, adds value to grain crops, and provides forages and crop residue. The integration can spread economic and production risk over several different enterprises and take advantage of a variety of agricultural markets. This is evident in various initiatives, such as the integration of oil palm cultivation with cattle farming from 2007 until now, the integration of cattle with cocoa crops from 2007 to 2010, the combination of cattle with sugarcane starting in 2009 until 2012, and the integration of cattle with coconut crops since 2013. Integrated farming systems, as described by Paramesh *et al*. (2020), represent an agricultural approach that combines activities in food crops, horticulture, livestock, fisheries, forestry, and other agricultural elements within a region simultaneously. This system is often implemented due to the increasing management inputs, presence of more enterprises, market challenges, and environmental concerns of consumers (Hendrickson *et al*., 2008). The farmer needs to manage the combination of agricultural commodities, different enterprises, and other complexities to achieve sustainable production. The principle of the sustainability of an integrated farming system comprises three dimensions, including economic, environmental, and social-community. Integrated agricultural systems can reduce the environmental impact of agriculture and increase adaptability, which is the greatest contributor to long-term sustainability. The correlation between the state-of-the-art analysis and knowledge gaps have been drawn in Fig. 1.

Compared to traditional farming models, this approach provides greater ecological and social advantages, including increased gains, higher input-output ratios, improved soil performance, and mitigation of the impacts of global warming (Yang *et al.,* 2022). The concept of sustainable agriculture has been subjected to development, initially focusing on ecological aspects, then expanding to include economic dimensions, and encompassing greater

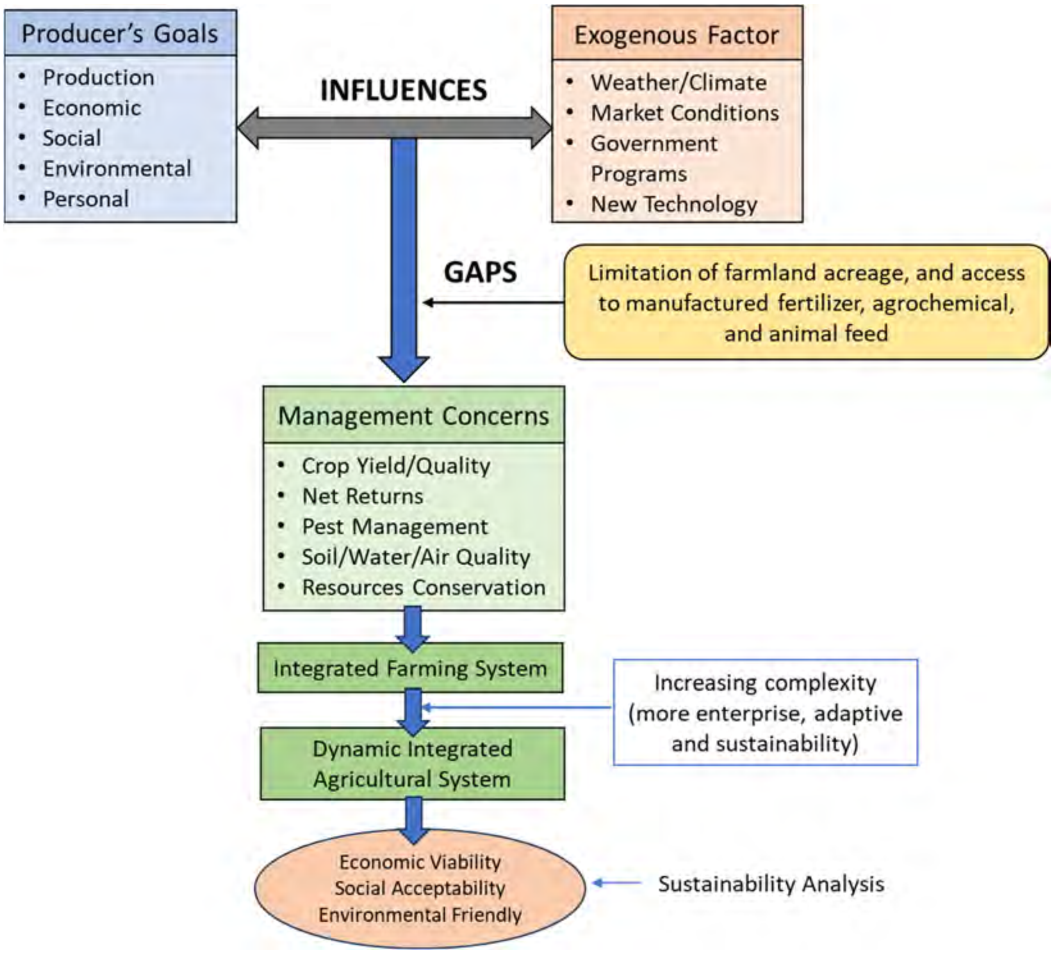

Fig. 1: The correlation between the state-of-the-art analysis and knowledge gaps (Tanaka *et al*., 2002)

social dimensions. Having less of an adverse influence on the environment and people's health, maximizing the utilization of local ecosystem resources, and preserving biodiversity are the core principles of sustainable agriculture (Asadi *et al.,* 2013). According to Suradisastra (2017), sustainable agricultural development must encompass various aspects, including technical, technological, socio-cultural, economic, and conservation (environmental). The implementation of the concept is the utilization of by-products or waste from each production subsystem as a source of livestock feed and fertilizer, thereby creating the concept of Low External Input Sustainable Agriculture (LEISA). The use of waste, specifically from the oil palm mill, such as solid oil palm, palm kernel meal, fiber, and boiler ash for fertilizer and animal feed has been previously reported (Grinnell *et al.,* 2022). The technology has been widely adopted by the community, and reported by several studies (Bremer *et al.,* 2020). Due to environmental issues with the composting of agricultural wastes, experts examine and develop a solid waste management plan employing alternative techniques. The solid waste industry has approved several techniques or procedures used in the previous 20 years to treat agricultural waste (Aziz *et al*., 2022). Different types of organic materials, including cellulose, hemicellulose, lignin, and starch, can be found in agricultural waste (Suhartini *et al.,* 2022). In high-income countries, the government typically covers the costs of trash processing (Rindhe *et al*. (2019)). However, this is not the case in low-income nations where more resources are needed to establish waste management infrastructure. Composting of agricultural waste can be evaluated for sustainability by computing the sustainability index using Multi-dimensional scaling (MDS). A multivariate statistical approach called multidimensional scaling is used as a variable to position items according to their similarities and differences. People's preferences or opinions are often transformed by MDS into multidimensional distances that can be scientifically described. MDS refers to a variety of statistical methods that compress preference data by visualizing the underlying relationships between groups (Wan *et al*., 2021). It has also been reported to have the ability to interpret and refine respondents' preferences or opinions concerning the agricultural integration production sustainability index theme. This study used five dimensions (environmental, social, economic, technological, and institutional) to provide suggestions and help decision-makers in sustainable development. It was also hypothesized that implementing integrated agricultural production can minimize pollution while also improving soil conditions. However, it was important to identify the most significant attribute for each of the environmental, social, economic, and technological dimensions. The MDS practical approach offers information to help decision-makers in the agricultural integration production with waste management. The study objectives are 1) measuring the overall sustainability index value, 2) calculating the sustainability index for each dimension: environmental, social, economic, technological, and institutional, and 3) examining important influences on integrated agricultural production systems. This study evaluates the feasibility of an integrated production supply system and was conducted in seven groups at the National Research and Innovation Agency and the Ministry of Agriculture, Republic of Indonesia, from 2022 to 2023.

MATERIALS AND METHODS

Study procedure

Experts and business operators engaged in the integrated production of organic fertilizer, corn, and laying hen farming conducted scientific assessments to gather primary and secondary data. This was carried out through Focus Group Discussions and the completion of a questionnaire containing 34 attributes linked to environmental, economic, social, technological, and institutional aspects. The data were analyzed using a multidimensional scale technique. Monte Carlo analysis and alternating least-squares algorithm were utilized to examine sustainability status and significant characteristics. Focus group discussions (FGD) were carried out to analyze the survey data, and six experts, including corn farmers, poultry farmers, organic fertilizer experts, and business actors, were surveyed. The qualifications of experts in filling out the questionnaire were those who had at least five years of experience in integrated production management. Furthermore, it was intended to evaluate the current business player environments and resource support for integration production for designing dimensions and attributes. The total number of attributes used in this study was 34 with five dimensions, namely environmental, social, economic, technological, and institutional. A questionnaire with response options using a Likert scale described these dimensions and attributes. The Expert respondents responded to the questionnaire questions by scoring 0 for poor, 1 for average, and 2 for good. Organic fertilizer in this activity was a mixture of ingredients from palm oil mill by-products consisting of fiber, solid palm oil, empty fruit bunches, and boiler ash, which were enriched by microbes. The results of the laboratorium analysis are presented in Table 1.

Data analysis

The MDS method was used in the data analysis through the Rap-integration technique (Rapid Appraisal for Integration Production). This technique was an adoption and development of the Rapfish (Rapid Appraisal for Fish) method to measure the sustainability of organic fertilizer production. The stages for determining a sustainability index are presented as follows (Lloyd *et al.,* 2022).

1) Assess each attribute of the sustainability dimension. This study had six dimensions with a total of thirty-four attributes.

2) Give a score to each attribute. A matrix X of size (n x p) was formed with attribute score elements, where n was the number of regions and their reference points, and p was the number of attributes, using Eq. 1 (Borg *et al.,* 2018).

Table 1. The result of laboratory examination of organic fertilizer based on palm oil mill by-product

No.	Types of Testing	Test methods	Test results
1	Potential of hydrogen (pH)	pH meter	11.12
2	Nitrogen (percent) (%)	Kjeldahl	0.40
3	Phosphorus (P) (%)	Spectrophotometry	1.42
4	Potassium (K) (%)	Atomic absorption spectrometry (AAS)	0.75
5	Sodium (Na) (%)	AAS	2.04
6	Calcium (Ca) (%)	AAS	4.80
7	Magnesium (Mg) (%)	AAS	1.06
8	Organic carbon (OC) (%)	Spectrophotometry	1.81
9	Iron (Fe) (ppm)	AAS	3,344.97
10	Copper (Cu) (ppm)	AAS	96.56
11	Manganese (Mn) (ppm)	AAS	318.76
12	Zinc (Zn) (ppm)	AAS	88.46
13	Lead (Pb) (ppm)	AAS	27.05
14	Sulphurous (S) (5%)	Spectrophotometry	0.30

$$X_{ik}sd = \frac{X_{ik} - X_k}{s_k} \quad (1)$$

where:

$X_{ik}sd$ = the i^{th} k^{th} attribute regional standard score (including reference points), where i = 1, 2, …, n and k = 1, 2, …, p

X_{ik} = the i^{th} k^{th} attribute standard score (including reference points), where i = 1, 2, …, n and k = 1, 2, …, p

X_k = the k^{th} attribute mean score, where k = 1, 2,…, p

S_k = the k^{th} attribute standard deviation score, where k = 1, 2, …, p

Eq. 2 (Borg *et al.,* 2018) was used to calculate the shortest distance according to the Euclidean distance. This distance was then converted into a two-dimensional Euclidean space, (d12) using the regression formula stated in Eq. 3 (Borg *et al.,* 2018). The ALSCAL algorithm was employed in the regression process to perform iterations until the intercept value in the equation reached zero (a=0). Therefore, Eq. 3 was transformed into Eq. 4 (Borg *et al.,* 2018). When the stress value (s) <0.25 was reached, the repetition process was stopped, and the S value was attained using Eq. 5 (Borg *et al.*, 2018).

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (2)$$

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (3)$$

$$d_{12} = bD_{12} + e; \quad (4)$$

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (5)$$

3) Assess and determine sustainability index and status. The sustainability status category for the sustainability of integrated production could be classified into four categories based on the sustainability index. These categories were highly (75.01-100.00), moderately (50.01-75.00), less (25.01-50.00), and not sustainable (0.00-25.00).

4) Conduct a sensitivity (leverage) analysis to measure the critical attributes that strongly influenced the sustainability of the integration production system. This analysis was based on the priority order of changes in the root mean square (RMS) ordination on the x-axis. When the RMS had a substantial value, it indicated that the function of this feature in determining sustainability was becoming more prominent (more sensitive).

5) Monte Carlo analysis was utilized in the Rap-

Integration technique to calculate the random error rate in the model produced from the MDS analysis for all dimensions at the 95% confidence level. The lesser the value difference between the MDS and Monte Carlo analysis findings, the better the Rap-Integration method's Monte Carlo model. In MDS, the values of S and the coefficient of determination (R^2) reflected the degree of fit. A low S value implied a favorable match, while a high S value indicated an unfavorable match. A solid Rap-fertilizer model had a S value smaller than 0.25. An R^2 number near one indicated that the qualities used to assess a dimension were reasonably accurate (Pitcher and Preikshot, 2001; Samimi *et al.,* 2023).

To evaluate sustainability, the multidimensional scaling (MDS) method had become widely used. Furthermore, it had been extensively utilized to evaluate the viability of producing various agricultural commodities. Table 2 shows previous analyses of agricultural product sustainability using the MDS approach.

Ecological/environmental, economic, social, technological, and institutional factors were the most frequently used in previous studies on sustainability.

Table 2: Previous study utilizing MDS analysis

No.	Title/topic study	Dimensions	Sources
1	MDS preference plot for agricultural data visualization analytics	social, environmental, economic	Zhang and Ding, 2023
2	Visual analytics of agricultural data by MDS preference plot	environmental, economic, social	Papilo *et al*., 2023
3	Policy-related Biodiesel Sustainability in Indonesia	economic, ecological, social	Dharmawan *et al*., 2020
4	Sustainability of plants and supporting facilities	ecological, economic, social	Giuntoli *et al*., 2022
5	Sustainability agricultural development	social, ecological, economic, institutional	Suardi *et al*., 2022
6	Sustainability of microalgal biomass production	ecological, social, economic, technological	Santoso *et al*., 2023a
7	Sustainability garlic production	environmental, technological, economic, social, and institutional dimensions	Paczka *et al*., 2021
8	The sustainable cultivation of cocoa	environmental, social, economic, institutional dimensions, and technological	Fairuzia *et al*., 2020
9	Sustainability of organic fertilizer production	environmental, social, economic, institutional dimensions, and technological	Santoso *et al*., 2023b
10	Sustainability corn production	environmental, technological, social, economic, and institutional dimensions	Ariningsih *et al*., 2021
11	Sustainability assessment of chili farming	environmental, economic, social, technological, and institutional dimensions	Mailena *et al*., 2021
12	Sustainable production of beef cattle	dimensions of the environment, society, economy, technology, and institutions	Kapa *et al*., 2019
13	Sustainability of dairy cattle production	dimensions of environmental, social, economic, technological, and institutional	Lovarelli *et al*., 2020
14	Sustainability buffalo production	environmental, economic, technological, and social dimensions	Rohaeni *et al.,* 2023
15	Sustainability shrimp production	dimensions of environmental, social, economic, technological, and institutional	Sivaraman *et al*., 2019
16	Sustainability coffee production	environmental, social, economic, and technical aspects	Yusuf *et al*., 2022
17	Sustainability rice production	institutional, environmental, social, economic, and technical aspects	Rachman *et al*., 2022
18	Sustainability of red chili production	technical, social, economic, and environmental aspects	Nuraini and Mutolib, 2023
19	Sustainability of black soldier fly production	social, economic, environmental, and technical aspects	Santoso *et al*., 2023c

Other studies carried out analysis using ethical, commercial, and political factors. Those studies had varied ideas on the number and types of metrics to be used.

RESULTS AND DISCUSSION

Dimension and attribute

The MDS approach was used to determine the amount of sustainability in integration manufacturing. The variables and qualities affecting sustainability were determined by extensively examining their effects on Integration production (Lloyd *et al.*, 2022). The study included 34 attributes across five dimensions, namely environmental, economical, social, technological, and institutional. The data used to calculate the MDS were obtained from a questionnaire, and Table 3 had a complete breakdown of the dimensions and attributes.

To get expert perspectives on the scientific viability of composting processes for manufacturing

Table 3: Dimensions and attributes of the low-input integrated agricultural farming sustainability

No.	Dimension	Attributes	
1.	Environmental	1. Effective use of biodegradable materials for the production of eggs and fertilizer 2. Effectiveness of using chemicals in the production of eggs and fertilizer 3. Effectiveness in the use of electrical energy and fuel during the production and marketing 4. Effectiveness in the use of water during egg and fertilizer production	5. Possibility of air pollution (odor generated) 6. Possibility of water pollution 7. Utilization of natural resources (land, biota, and plants) in the production of eggs and fertilizer 8. Potential for illness to spread because of the integration industry 9. Possibility that the integration industry will harm biodiversity
2.	Social	10. Industry manager or entrepreneur's level of education 11. Family members working in the integration industry 12. Level of business motivation 13. Possibility of public unrest due to the integration industry 14. Possibility of losing other jobs because of the integration industry	15. Managerial or employee-level expertise in the conservation and restoration of the environment 16. Risk of workplace accidents 17. Possibility of creating jobs for the community
3.	Economical	18. Productivity level of the integration industry 19. Management level of the integration industry 20. Possibility of increase in business scale/business success rate e	21. Enhancing the welfare of managers and employees 22. Efficiency in using raw materials and the simplicity with which raw materials can be obtained for the integration industry 23. Market penetration of the integration industry
4.	Technological	24. Part of the community's ability to quickly adopt the integration industrial system 25. Partially required specialization, experience, and/or skill set for managers in the people's integration industry	26. Availability of integration industry facilities and infrastructure 27. Possibility of increasing integration production 28. Sensitivity of the technical/method to the level and scope of the integration industry
5.	Institutional	29. The actuality of the manager of this integration activity 30. The actuality of integration business rules from the government 31. Availability of assistance from the authorities/government	32. The actuality of a group of fellow entrepreneurs/managers 33. The actuality of financial institutions that help 34. The actuality of marketing agencies

organic fertilizer, the characteristics within each dimension were compiled into a questionnaire and distributed to the appropriate professionals. The Rapfish program and the MDS technique were used to examine the results of these professional reviews. The sustainability ratings for each dimension are shown in Table 4.

Environmental carrying capacity, production input accessibility, production techniques, processing, egg, corn, and fertilizer marketing, and the responsibilities of relevant organizations were factors with a long-term impact on integrated production. Furthermore, integration production systems could replace conventional animal feed production as an economically and environmentally sound alternative by considering these aspects and implementing sustainable methods (Rehman *et al*., 2020). The results of the MDS study on the creation of environmentally friendly integrated production were given in Fig. 2 with a stress value of 0.15 (stress 50%). This demonstrated the reliability and precision of the five dimensions calculated by the Monte Carlo test. The integration production system had a sustainability value of 86.10. The social dimension had the highest level of sustainability, while the technological dimensions had a fair sustainability category, as illustrated in Table 4.

Table 4 showed the results of running the validity of the MDS analysis findings at the 95% confidence level, as determined by the goodness of fit value, namely the stress value and R^2. The stress value quantified the difference between the model and the real data. The R^2 value was a measure of precision that assessed the model's capacity to explain fluctuations in the dependent variable (Leven *et al*., 2023; Samimi and Mansouri, 2024). The stress value (0.136-0.144) in Table 4 was less than 0.25, showing that the model was close or similar to the actual scenario due to the low mismatch value. Meanwhile, the coefficient of determination (R^2) ranged between 0.936-0.949. The higher the value was closer to 1, the higher the quality of the analysis performed. It indicated that additional attributes were not required in the case studied, and the aspects analyzed were accurately close to the actual conditions (Saputro *et al.,* 2023). According to Suardi *et al.,* 2022, all attributes used in the analysis of the sustainability of the production process through the integration of organic fertilizers corn

Table 4: The sustainability index for all dimensions

Dimension	Index (%)	Stress	R^2(SQR)	Status
Environmental	83.45	0.136	0.947	good sustainable
Social	93.79	0.137	0.949	good sustainable
Economical	90.57	0.136	0.946	good sustainable
Technological	74.29	0.144	0.936	fairly sustainable
Institutional	88.39	0.143	0.941	good sustainable
Average	86.10			good sustainable

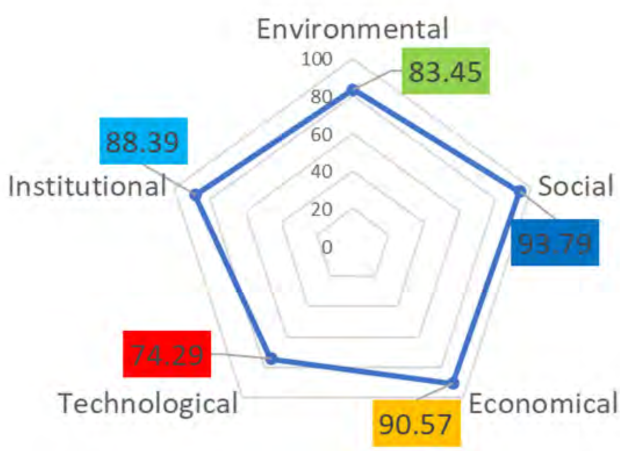

Fig. 2: The level of sustainability achieved in integration production

cultivation, and layer hen farming on dry land in the Pangkalan Lada Subdistrict were good at explaining the five dimensions analyzed. The foregoing results could also be interpreted as indicating that the model produced was good and accurately described the topic under consideration (Rachman *et al*., 2022).

Environmental dimension

According to Asadi *et al*. (2013), the environmental dimension had a substantial impact on sustainable agriculture. This activity's sustainability assessment for the environmental dimension included nine attributes, which were listed in Table 3. The results showed that the environmental component had an index value of 83.45%, a stress value of 0.136, and a structured query reporter (SQR) value of 0.947, indicating the achievement of (Table 4). This was a commendable index achievement that merited future enhancement. It showed that the production process in Pangkalan Lada Subdistrict had considered environmental preservation and ecosystem balance by including organic fertilizers, corn cultivation, and layer hen farming on dry land. This was understandable given the implementer's prior experience with implementing Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) in managing oil palm plantations (Widiati *et al.,* 2020). The dimension was positively rated in the context of sustainability since ISPO and RSPO were used in their management (Afrino *et al.,* 2023). Based on the attribute leverage analysis results for the environmental dimension show that two attributes, namely Efficiency in the use of water during egg and fertilizer production and Efficiency in the use of electrical energy and fuel during production and marketing had RMS values of 7.88 and 7.25 respectively (Fig. 3). These findings had a substantial impact on the sustainability of this

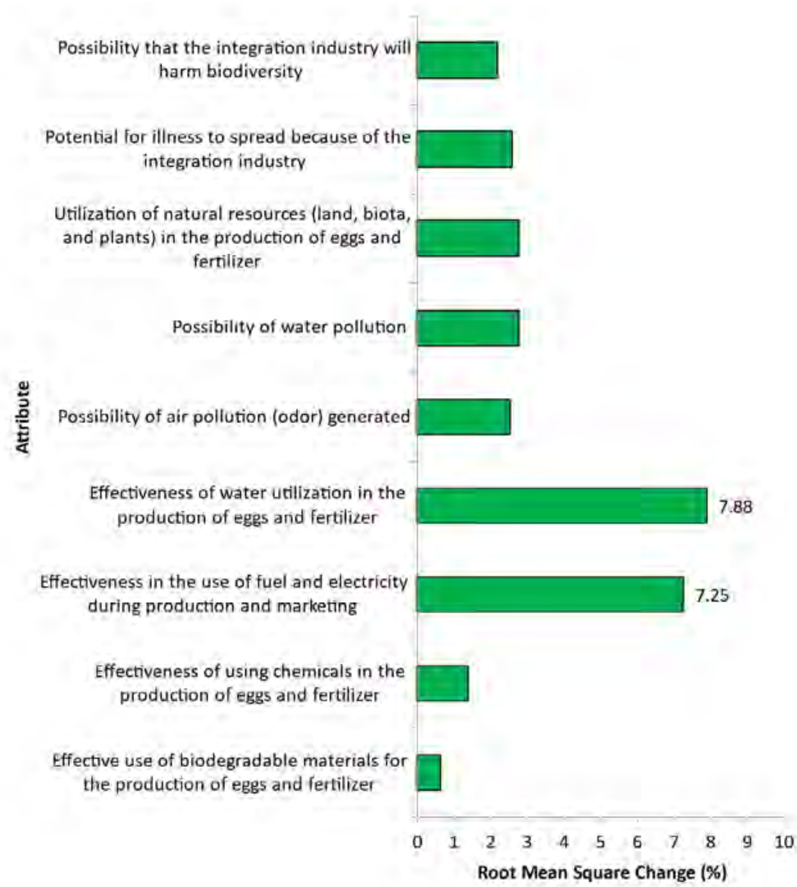

Fig. 3: Leverage of environmental attributes

activity in the context of the environment. To reach a high level of sustainability, it was necessary to improve the management of these traits. The values of the other attributes had no substantial impact, but attention must still be taken to ensure the preservation of the environmental dimension within the context of sustainability. In the environmental dimension of agricultural activities, efficiency had become a sensitive issue (Asadi *et al*., 2013). Regarding the efficient use of electrical energy and fuel, the potential of palm oil mill waste on site, aside from animal feed (Wadchasit *et al.,* 2021) and fertilizer should be considered for its utilization as an electricity resource (Mahidin et al., 2020) and a fuel, such as biogas (Tiong *et al*., 2021). Several studies had shown that community waste could be transformed into electricity (Abdoli *et al*., 2012). The use of liquid waste for other purposes in the agricultural industry was an important topic in environmental sustainability. It was important to recycle and reuse wastewater to meet future human demand and reduce water scarcity, as well as ensure compliance with wastewater discharge standards for environmental sustainability while minimizing groundwater and soil contamination.

Social dimension

The sustainability assessment for the social dimension using eight attributes is presented in Table 3. The results indicated that the social aspect had an index value of 93.79%, a SQR score of 0.949 with a stress value of 0.137, indicating the fulfillment of the criteria (Table 4). Compared to the environmental dimension status, it had a good index, which was worthy of being maintained and improved. The indicator showed that the production process in this activity carried out in the dry lands of the Pangkalan Lada sub-district, had a good social involvement in the sustainability of this activity. Compared to other dimensions, the social element had the highest sustainability index among the five aspects. A similar finding was reported by Surahman *et al*. (2018),

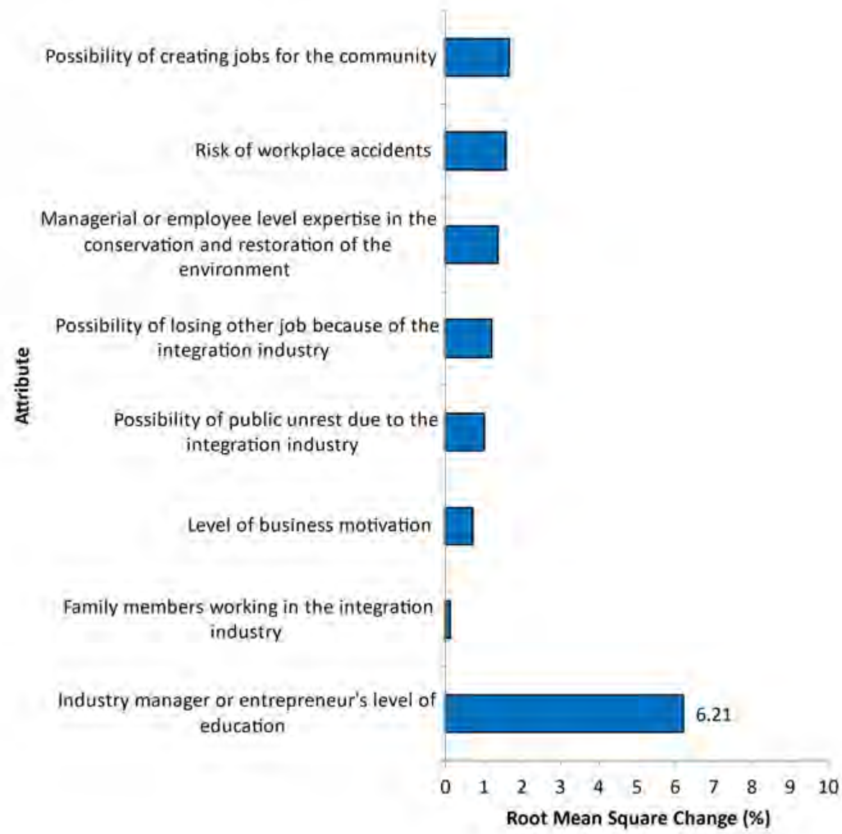

Fig. 4: Leverage of social attributes

where the social dimension had the highest value for peat land farming. According to Surahman *et al*. (2018), this activity was thought to be due to the establishment of the use of land for agriculture. The results of social sustainability dimensions in Fig. 4 indicated that out of the eight attributes reviewed, one sensitive attribute influencing the sustainability of this activity was the level of education of industry managers or entrepreneurs. Education level in this context was not limited to formal education but also emphasized the accumulation of experience and acquired information. For example, the intensity of counseling, training, and experience could have a significant impact on the success of implementing this activity. These findings were consistent with Asadi *et al.* (2013) who also obtained similar results, In terms of social capital, sustainable agriculture was frequently related to farmer engagement, contentment, technical knowledge, farmer competencies, and social capital. The analysis conducted by Osak and Hartono (2016) suggested that in the social dimension of agricultural integration systems in the livestock and horticulture sector, related to attitudes, responses, and perceptions, improvement was needed through counseling, training, and field demonstrations (demonstration plots) to enhance its social sustainability. In line with the report by Mailena *et al*. (2021), the intensity of counseling, training, and formal education for farmers had a sensitive impact on the sustainability of chili farming. Leven *et al*. (2023) also reported that in the social dimension, attributes, such as the frequency of counseling and training were the most important factors determining the sustainability of milkfish farming activities in Gresik Regency. Training could provide experience and bring out creativity (Janker and Mann, 2020).

Five dimensions (social, environmental, economic, technological, and institutional) with 34 attributes in the integration of organic fertilizers, corn cultivation, and laying hen farming, influenced each other on the sustainability of this integrated farming (Bathaei and Štreimikiene (2023). The integration of the 5 dimensions led to long-term oriented agricultural production, which was economically feasible and did not damage the environment through good management and governance (Sadiku *et al.,* 2021). Furthermore, it was described in each attribute and in each dimension within the integration of organic fertilizers, corn cultivation, and laying hen farming.

Economical dimension

The level sustainability assessment for the economic sector, as presented in Table 3, utilized six attributes. The findings showed that the economic dimension had an index value of 90.57% , a stress value of 0.136, and an SQR value of 0.946, and they met the sustainability criteria (Table 4). This index held a favorable status and was worthy of preservation and further enhancement. Based on these findings, the production process through the integration of organic fertilizers, corn, and layer hen farming in the dry lands of Pangkalan Lada sub-district had sustainable economic value. The presence of agribusiness in the integration system in the study area, as mentioned by Sulistyono *et al.* (2019), was highly beneficial from an economic perspective. These results were inconsistent with Li *et al.* (2020) in the context of monoculture layer chicken farming, where the economic dimension was not sustainable. The note of the leverage attribute analysis for the economical dimension indicates that one attribute, namely the level of ease of getting raw materials for the integration industry (Fig. 5), had a highly significant influence on the sustainability of this activity. In line with Fu *et al.* (2021) and Lin *et al.* (2022), material production was the highest leverage attribute. Efforts to obtain raw materials were crucial to achieve a high level of sustainability. The raw materials referred to in this activity were those used in the production of organic fertilizers and layer feed and were obtained from the palm oil mill in terms of their by-product. The by-product used to make organic fertilizer was fiber, namely 26% from fresh fruit bunches, which were processed into CPO, solid palm oil (3%), empty fruit bunches (16%), and boiler ash. Meanwhile, the by-product used to feed laying hens was palm kernel meal, and it was produced at 4%. These feed ingredients were formulated into alternative feed for laying hens that were tailored to the chicken's nutritional needs, leading to a cost-effective alternative feed. Supporting the local government in obtaining these materials was essential because an official letter of endorsement from the Local Government, which could be provided by the relevant department, was required to access them. According to Bathaei and Štreimikiene (2023), the government could also assist companies in reducing

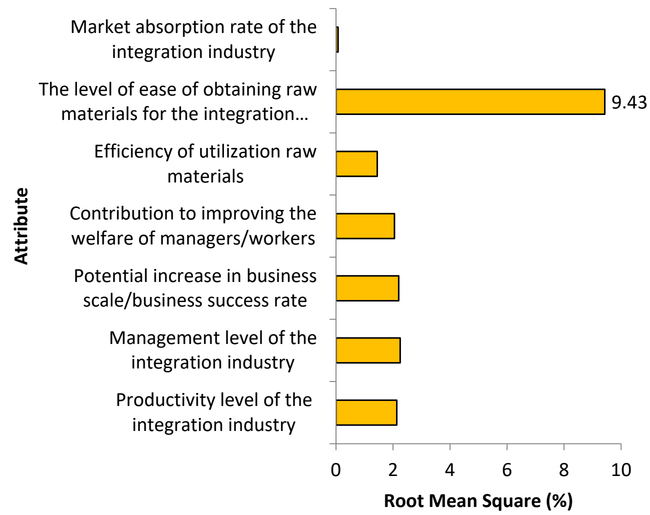

Fig. 5: Leverage of economical attributes

the prices of raw materials and facilitating farmers in purchasing recycled products (by-products). In relation to livestock farming activities, feed played a crucial role as it accounted for 60-70% of production costs (Wongnaa *et al*., 2023). This was evident from the analysis results that raw materials were a primary factor in the economic dimension. Similar findings had been reported by Sulistyono *et al*. (2019) concerning the availability of animal feed, and by Jasmawadi *et al*. (2022) regarding the availability of production raw materials as key drivers in sustainable economic dimensions. Although other attributes did not have significant impacts, attention was still necessary to maintain the economic dimension within the context of sustainability.

Technology dimension

The sustainability assessment for the technology dimension, using five leverage points (Table 3) indicated that it exhibited a fairly good level of sustainability, with an index value of 74.29%. The index value for the technology dimension was lower compared to the index of others. Therefore, serious attention was needed to enhance its sustainability. The stress and SQR both had good values, namely 0.144 and 0.936, respectively (Table 4). Developing an integrated agricultural system required the application of appropriate technology (Paramesh *et al*. (2020). During the use of agro-industry waste, such as palm oil mill waste, there was a need to implement biotechnology to ensure further usage, including fermentation with microbes (Sivakumar *et al*., 2022). The implementation of technology was crucial as it had a positive correlation with the food security of household farmers (Mutenje *et al*., 2016) and farmers' income (Lin and Wu, 2021). Furthermore, it promoted the sustainable and resilient growth of food productivity (Hailu, 2023). The results of the attribute leverage analysis for the technology dimension indicated that there were three attributes with significant influence on the sustainability of this activity, namely; 1) the potential for increasing integration production, 2) the availability of integration industry facilities, and 3) the level of specialization required for managers of the people's integration industry (Fig. 6). Therefore, the technological aspect must receive special attention in efforts to enhance the sustainability of this activities from a technological perspective. Farmers could not typically change the conditions of their farming operations without guidance and support from individuals who possessed expertise in this field and they must be supported by emerging technologies. This task was to be undertaken by agricultural extension workers. In the technology adoption process, the pattern of extension workers included serving as facilitators, motivators (Wedajo *et al*., 2019), consultants, and technical assistants (Indraningsih *et al*., 2023). One of the factors influencing the rapid adoption of agricultural

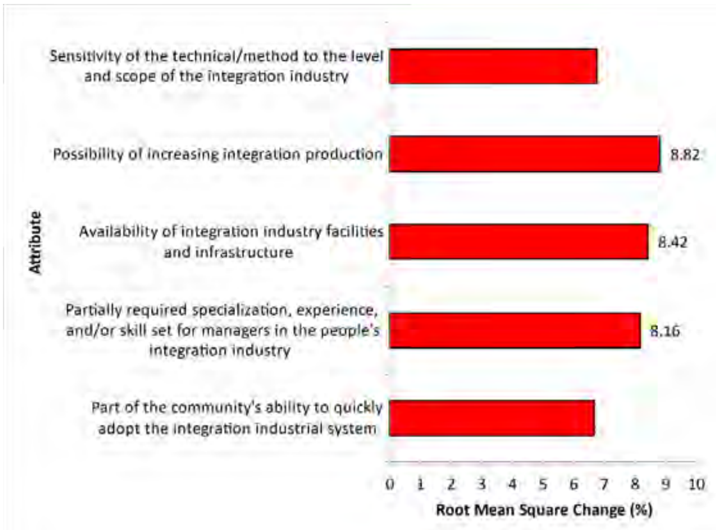

Fig. 6: Leverage of technology attributes

technology innovations by users or farmers was the choice of the type of extension media. Spectrum Dissemination Multi-Channel Spectrum represented an innovation (IAARD, 2011) aimed at expediting and broadening the optimal dissemination reached through various media simultaneously and in a coordinated manner. Furthermore, its effectiveness had been proven in driving the diffusion of technology innovations to users (Bounadi *et al.,* 2022).

Institutional dimension

The institutional dimension was also sustainable, as the sustainability index reached 88.39% with a stress value of 0.143 and an SQR value of 0.936 (Table 4). Institutions in the agricultural sector played an essential role in making the hopes, desires, and needs of farmers come to fruition (Musafiri et al., 2022). These rural farmer organizations were instrumental in advancing the socio-economic advancement of farmers, as they provided access to vital agricultural information, facilitating their access to capital, infrastructure, and markets, as well as promoting the adoption of innovative agricultural practices. The presence of farmer institutions helped to facilitate the government and other stakeholders in their efforts (Šūmane, 2018). The institutional dimension was sustainable, indicating that the institutions were independent. In this situation according to Provotorina *et al.* (2020), institutions functioned as production units and providers of production facilities. This condition was appropriate in the field due to the formation of farmer groups and Village Cooperative Units: Koperasi Unit Desa (KUD), where business units of KUD included those dedicated to agricultural production, savings and loans, and the provision of agricultural production facilities. Therefore, agricultural activities, particularly capital, were not a problem. Based on Fig. 7, the presence of financial institutions providing support was among the six leverage attributes in the institutional dimension that influenced the sustainability of this activity. The sensitivity of this attribute was highly significant compared to other attributes, indicating that financial institutional support had a substantial impact on the sustainability of the production process in the integration of organic fertilizer, corn, and layer hen farming. The key starting point related to finances was also reported by Khaerunnisa *et al*. (2023) and Ningsih *et al*. (2021).

It was suggested that the Indonesian government implement the following actions: 1) Rules and rewards: The government could promote regulations that assisted effective trash management, possibly providing rewards for eco-friendly actions, such as composting and waste conversion; (2) Financial Boost: Offering financial assistance, subsidies, or grants to promote the production of organic fertilizer by farmers, cooperatives, or companies; (3) Building capacity: Government-led training programs to inform participants on the benefits of composting,

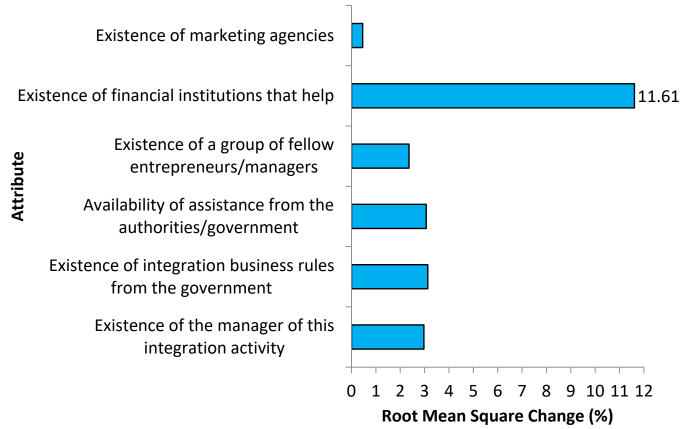

Fig. 7: Leverage of institutional attributes

organic fertilizer, and waste management best practices; (4) collaboration could increase knowledge, resources, and scaling potential through public-private partnerships involving the commercial sector, NGOs, and international organizations.

CONCLUSIONS

In conclusion, the sustainability index for environmentally low-input integrated farming that included activities of organic fertilizer, corn, and layer hen farming was determined using the MDS method. Furthermore, it considered factors affecting sustainability across five dimensions, namely environmental, social, economic, technological, and institutional dimensions. The sustainability index was estimated to be 86.10% (good sustainable), hence, the process had the potential for sustained development when the leverage factors described in each dimension were considered. These findings suggested that integrated farming comprising organic fertilizer, corn, and layer hen farming in the dry lands of the Pangkalan Lada sub-district had successfully integrated the potential of existing resources to realize sustainable agriculture and the potential to be applied in other locations in the future. Due to diverse regional characteristics, the developed sustainability index was valid and limited in the area where it was developed. The technological dimension had the lowest leverage value at 74.29%, while that of environmental, social, economic, and institutional were determined at 83.45%, 93.57%, 90.57%, and 88.39% respectively. Therefore, efforts to enhance the sustainability of these agricultural activities must primarily focus on the technological dimension, with an emphasis on 1) the potential for increasing integration production, 2) the availability of integration industry facilities, and 3) the level of specialization required for managers of the people's integration industry. Improving the economic aspects was prioritized, particularly those related to getting raw materials for the integration system. Support from the local government in obtaining raw materials was essential to maintain integrated farming. In terms of the environmental dimension, enhancing water during egg and fertilizer production and electric efficiency during production and marketing were essential factors. In the social dimension, addressing factors, such as job security, community engagement, and knowledge levels of workers and managers was identified as crucial for achieving sustainable implementation. Strategies, such as retraining, stakeholder engagement, communication, and capacity-building were deemed essential for promoting community well-being and fostering sustainable low-input integrated farming. For the institutional dimension, it was highly significant compared to other attributes, indicating that financial institutional support had a substantial impact on the sustainability of low-input integrated farming. Furthermore, it was emphasized that government support and technological considerations were essential for promoting environmentally low-input integrated farming in Indonesia, specifically given the escalating demand for producing egg and organic fertilizers using an integrated farming approach.

AUTHOR CONTRIBUTIONS

E. Widjaja prepared the manuscript, and critically analyzed the manuscript's crucial substantive value; B.N. Utomo performed recognition of data, and experimental operation; A.D. Santoso prepared the manuscript and critically analyzed the manuscript's crucial substantive value; Y.P. Erlambang performed recognition of data and handed material and operational support; Surono supervised manuscript preparation; M.A. Firmansyah prepared the manuscript, and critical revisions; S. Handoko performed recognition of data; E. Erythrina performed data curation; M.N. Rofiq performed experimental operate, and elaboration of MDS data; D. Iskandar performed prepared the manuscript and critically analyzed the manuscript's crucial substantive value; N.A. Sasongko recognized data and information and critically analyzed the manuscript's crucial substantive value; T. Rochmadi performed recognition of data; N. Abbas performed the literature review; M. Hanif performed recognition data and prepared the manuscript; Y.S. Garno prepared the manuscript; F.D. Arianti prepared the manuscript and made critical revisions; N.D. Suretno performed recognition data; M. Askinatin performed recognition data and prepared the manuscript; C.O.I. Hastuti performed administrative tasks; M. Fachrodji handed material and operational support.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
AAS	Atomic Absorption spectrometry
C	Carbon
Ca	Calcium
Cu	Cupper
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point
d_{ijk}	Squared distance
Fe	Iron
FGD	Focus group discussions
ISPO	Indonesian sustainable palm oil
K	Potassium
KUD	Village cooperative units
LEISA	Low external input sustainable agriculture
MDS	Multidimensional scaling
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium

N	Nitrogen
OC	Organic carbon
P	Phosphorus
Pb	Lead
pH	Potential of hydrogen
K	Potassium
R^2	Coefficient of determination
Rapfish	Rapid appraisal for fisheries, an analytical method to assess the sustainability of fisheries based on a multidisciplinary approach
RMS	Root mean square, a frequently used measure of the differences between values
RPJMN	National Medium-Term Development Plan
RPJPN	National Long-Term Development Plan
RSPO	Roundtable on Sustainable Palm Oil
SQR	Structured query reporter, a programming language designed for generating reports from database management systems
SR2	Squared correlation
S	Sulphurous
x-axis	Horizontal number line
y-axis	Vertical number line
Zn	Zinc

REFERENCES

Abdoli, M.A.; Karbassi, A.R.; Samiee-Zafarghandi, R.; Rashidi, Zh.; Gitipour, S.; Pazoki M., (2012). Electricity Generation from leachate treatment plant. Int. J. Environ. Res., 6(2): 493-498 **(6 pages).**

Afrino, R., Syahza, A.; Heriyanto, M., (2023). Analysis of nuclear-plasma partnership pattern for sustainable oil palm plantation in Riau Province, Indonesia. Int. J. Sustainable Dev. Plann., 18(1): 91-98 **(8 pages).**

Archer, D.W.; Franco, J.G.; Halvorson, J.J.; Pokharel, K.P., (2019). Integrated farming systems. Encyclopedia of Ecology. 4: 508–514 **(7 pages).**

Ariningsih, E.; Rachman, B.; Sudaryanto, T.; Ariani, M.; Septanti, K.S.; Adawiyah, C.R., (2021). Strategies for sustainable corn production: A case of South Lampung District, Lampung Province, Indonesia. IOP Conference Series: Earth Environ. Sci., 892: 012075 **(8 pages).**

Asadi, A.; Kalantari Kh.; Choobchian, Sc., (2013). Structural analysis of factors affecting agricultural sustainability in Qazvin Province, Iran. J. Agric. Sci. Technol., 15: 11-22 **(12 pages).**

Aziz, H.A.; Lee, W.S.; Hasan, H.A.; Hassan, H.M.; Wang, L.K.; Wang, H.M.S.; Hung, Y.T., (2022). Composting by Black Soldier Fly. Solid Waste Engineering and Management. Handbook of Environmental Engineering Book Series, Volume 3. Springer.

Bathaei, A.; Štreimikienė, D., (2023). A systematic review of agricultural sustainability indicators. Agriculture. 13(241): 1-19 **(19 pages).**

Bell, L.W.; Moore, A.D., (2012). Integrated crop-livestock systems in Australian agriculture: Trends, drivers and implications. Agric. Syst., 111: 1-12 **(12 pages).**

Borg, I.; Patrick, J.F.; Groenen; Mair, P., (2018). Applied Multidimensional Scaling and Unfolding. Springer Cham.

Bounadi, I.; Allali, K.; Fadlaoui, A.; Dehhaoui, M., (2022). Can environmental regulation drive the environmental technology diffusion and enhance firms' environmental performance in developing countries? Case of olive oil industry in Morocco. Sustainability. 14(22): 15147 **(18 pages).**

Bremer, J.A.; de Bruyn, L.A.L.; Smith, R.G.B.; Cowley, F.C., (2022). Knowns and unknowns of cattle grazing in oil palm plantations. A review. Agron. Sustainable Dev., 42(17): 1-20 **(20 pages).**

Dharmawan, A.H.; Fauzi, A.; Putri, E.I.; Pacheco, P.; Dermawan, A.; Nuva, N., Amalia, R.; Sudaryanti, D.A., (2020). Bioenergy policy: The biodiesel sustainability dilemma in Indonesia. Int. J. Sustainable Dev. Plann., 15(4): 537-546 **(10 pages).**

Fairuzia, N.; Krisnamurthi, B.; Rifin, A., (2020). Analysis of sustainability status of cocoa plantation smallholders. IOP Conference Series: Earth Environ. Sci., 486: 012001 **(8 pages).**

Fu, B.; Stafford-Smith, M.; Wang, Y.; Wu, B.; Yu, X.; Nan, L.; Ojima, D.S.; Yihe, L.; Fu, C.; Liu, Y.; Niu, S.; Zhang,Y.; Zeng, H.; Liu, Y.; Liu, Y.; Feng, X.; Zhang, L.; Wei, Y.; Xu, Z.; Li, F.; Cui, X.; Diop, S.; Chen, X., (2021). The Global-DEP conceptual framework— research on dryland ecosystems to promote sustainability. Curr. Opin. Environ. Sustainable. 48: 17-28 (**11 pages**).

Giuntoli, J.; Barredo, J.I; Avitabile, V.; Camia, A.; Cazzaniga, N.E.; Grassi, G.; Jasinevičius, G.; Jonsson, R.; Marelli, L.; Robert, N.; Agostini, A.; Mubareka, S., (2020). The quest for sustainable forest bioenergy: win-win solutions for climate and biodiversity. Renewable Sustainable Energy Rev., 159: 112180 (**20 pages**).

Grinnell, N.A.; van der Linden, A.; Azhar, B.; Nobilly, F.; Slingerland, M., (2022). Cattle-oil palm integration – a viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability. Livest. Sci., 259: 104902 **(14 pages).**

Hailu, G., (2023). Reflection on technological progress in the agri-food industry: Past, present, and future. Can. J. Agric. Econ., 71: 119-141 **(23 pages).**

Hariyanti, F.; Syahza, A.; Zulkarnain; Nofrizal., (2022). Sustainability of the palm oil industry: An empirical study of sustainable oil palm development in Bengkalis Regency, Indonesia. Int. J. Sustainable Dev. Plann., 17(1): 109-118 **(10 pages).**

Hendrickson, J.R.; Liebig, M.A.; Sassenrath, G.F., (2008). Environment and integrated agricultural systems. Renewable Agric. Food Syst., 23(4): 304-313 **(10 pages).**

Indraningsih, K.; Ashari, A.; Syahyuti, S.; Anugrah, I.; Suharyono, S.; Saptana, S.; Iswariyadi, A.; Agustian, A.; Purwantini, T.; Ariani, M.; Mardiharini, M., (2023). Factors influencing the role and performance of independent agricultural extension workers in supporting agricultural extension. Open Agric., 8(1): 20220164 **(17 pages).**

Janker, J.; Mann, S., (2020). Understanding the social dimension of sustainability in agriculture: A critical review of sustainability assessment tools. Environ. Dev. Sustainability. 22**:** 1671-1691 **(21 pages).**

Kapa, M.M.J.; Hasnudi; Henuk, Y.L., (2019). Measuring technology sustainability status of local beef cattle under extensive rearing systems in the dryland area, Indonesia. IOP Conference Series: Earth Environ. Sci., 260: 012018 **(5 pages)**.

Khaerunnisa; Wahyuni MS, E.; Rukmana, D.; Egra, S.; Masitah; Fitriani, R.; Wulandary, A., (2023). Is agricultural institutions affect the sustainability of local *Adan Rice* farming?. Indigenous Agric., 1(1): 18-28 **(11 pages).**

Leven, W.A.; Liufeto, F.C.; Pasaribu,W., (2023). Sustainable development strategy of milkfish (*Chanos chanos*) aquaculture using the SWOT and QSPM approach : A study in Fahiluka, Malaka Regency, East Nusa Tenggara. IOP Conference Series: Earth Environ. Sci., 1224: 012004 **(8 pages).**

Lin, B.; Wu, C.C., (2021). Study on the impact of agricultural technology progress on grain production and farmers' income. Open Access Lib. J., 8(11): 1-9 **(9 pages).**

Li, N.; Ren, Z.; Li, D.; Zeng, L., (2020). Review: Automated techniques for monitoring the behaviour and welfare of broilers and laying hens: Towards the goal of precision livestock farming. Animal. 14(3): 617-625 **(9 pages).**

Lin, S.H.; Zhang, H.; Li, J.H.; Ye, C.Z.; Hsieh, J.C., (2022). Evaluating smart office buildings from a sustainability perspective: A model of hybrid multi-attribute decision-making. Technol. Soc., 68: 101824 **(14 pages).**

Lloyd, C.; Ananthan, P.S.; Ramasubramanian, V.; Sugunan, V.V.; Panikkar, P.; Landge, A.T., (2022). Rapid reservoir fisheries appraisal (r-RAPFISH): Indicator based framework for sustainable fish production in Indian reservoirs. J. Cleaner Prod., 379: 134435 **(17 pages).**

Lovarelli, D.; Bacenetti, J.; Guarino, M., (2020). A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production?. J. Cleaner Prod., 262: 121409 (**13 pages**).

Mahidin; Saifullah; Erdiwansyah; Hamdani; Hisbullah; Hayati, A.P.; Zhafran, M.; Sidiq, M.A.; Rinaldi, A.; Fitria, B.; Tarisma, R.; Bindar, Y., (2020). Analysis of power from palm oil solid waste for biomass power plants: A case study in Aceh Province. Chemosphere. 253: 126714 **(18 pages).**

Mailena, L.; Sirnawati, E.; Widjaja, E.; Ibrahim, T.; Nurfaida., (2021). Sustainability assessment of chili farming in the highlands of Pacet Sub District, Regency of Cianjur, West Java. IOP Conference Series: Earth Environ. Sci., 807: 032049 **(10 pages).**

Ministry of Agriculture, (2021). Ministry of Agriculture Strategic Plan 2020-2024. Agriculture Ministry.

Musafiri C.M.; Kiboi, M.; Macharia, J.; Ng'etich, O.K.; Kosgei, D.K.; Mulianga B., Okoti, M.; Ngetich, F.K., (2022) Adoption of climate-smart agricultural practices among smallholder farmers in Western Kenya: Do socioeconomic, institutional, and biophysical factors matter? Heliyon. 8(1): 1-8 **(8 pages)**.

Mutenje, M.; Kankwamba, H.; Mangisonib, J.; Kassie, M., (2016). Agricultural innovations and food security in Malawi: Gender dynamics, institutions and market implications. Technol. Forecasting Soc. Change. 103: 240-248 **(9 pages).**

Nashr, F.; Putri, E.I.K.; Dharmawan, A.H.; Fauzi, A., (2021). The sustainability of independent palm oil smallholders in multi-tier supply chains in East Kalimantan Indonesia. Int. J. Sustainable Dev. Plann., 16(4): 771-781 **(11 pages).**

Ningsih, W.W.; Iskandar, R.; Kasutjianingati, K., (2021). Sustainable dimensional status analysis in dragon fruits agribusiness development in Banyuwangi. Proceedings of the 2nd International Conference on Social Science, Humanity and Public Health. 645: 131-136 **(6 pages).**

Nuraini, C.; Mutolib, A., (2023). The sustainability analysis of red chili farming in Taraju District, Tasikmalaya Regency. IOP Conference Series: Earth. Environ. Sci., 1133 **(8 pages).**

Osak, R.E.M.F.; Hartono, B., (2016). Sustainable status assessment (SAA) in the integrated farming system of dairy-cattle and horticultural-corps in Indonesia. Int. J. ChemTech Res., 9(8): 575-582 **(8 pages).**

Pacini, C.; Wossink, A.; Giesen, G.; Vazzana, C.; Huirne, R., (2023). Evaluation of sustainability of organic, integrated and conventional farming systems: A farm and field-scale analysis. Agric. Ecosyst. Environ., 95(1): 273-288 (**16 pages**).

Paczka, G.; Mazur-Pączka, A.; Garczyńska, M.; Kostecka, J.; Butt, K.R. Garlic (Allium sativum L.) Cultivation using vermicompost-amended soil as an aspect of sustainable plant production. Sustainability. 13(24): 13557 (**11 pages**).

Papilo, P.; Marimin, M.; Hambali, E.; Machfud, M.; Yani, M.; Asrol, M.; Mahmud, J., (2022). Palm oil-based bioenergy sustainability and policy in Indonesia and Malaysia: A systematic review and future agendas. Heliyon. 8(10): 10919 **(17 pages).**

Paramesh, V.; Ravisankar,N.; Behera, U.; Arunachalam, V.; Kumar, P.; Solomon, R.; Dhar Misra, S.; MohanKumar, R.; Prusty, A. K.; Jacob, D.; Panwar, A.S.; Mayenkar, T.; Reddy, V.K.; Rajkumar, S., (2022).Integrated farming system approaches to achievefood and nutritional security for enhancingprofitability, employment, and climate resilience inIndia. Food Energy Secur., 11: e321 (**16 pages**).

Pitcher, T.J.; Preikshot, D., (2001). RAPFISH: A rapid appraisal technique to evaluate the sustainability status of fisheries. Fish. Res., 49(3): 255-270 **(16 pages).**

Provotorina, V.; Kazmina, L.; Petrenko, A.; Ekinil, G., (2020). Organization and functioning of accommodation facilities as a component of rural tourism infrastructure in the Rostov Region. E3S Web Conference. 175: 10002 **(12 pages).**

Rachman, B.; Ariningsih, E.; Sudaryanto, T.; Ariani, M.; Septanti, K.S.; Adawiyah, C.R.; Ashari; Agustian, A.; Saliem, H.P.; Tarigan, H.; Syahyuti; Yuniarti, E., (2022). Sustainability status, sensitive and key factors for increasing rice production: A case study in West Java, Indonesia. PLoS One. 17(12): 1-19 **(19 pages).**

Rehman, S.; Aslam, Z.; Belliturk, K.; Ahmad, A.; Nadeem, M.; and Waqas, M. (2020). Vermicomposting in Pakistan: Current scenario and future prospectives. Mod. Concepts Dev. Agron., 6(1): 617-619 **(3 pages).**

Rindhe, S.N.; Chatli, M.K.; Wagh, R.; Kaur, A.; Mehta, N.; Kumar, P.; Malav, O.P., (2019). Black soldier fly: A new vista for waste management and animal feed. Int. J. Curr. Microbiol. App. Sci., 8(1): 1329–1342 **(14 pages).**

Rohaeni, E.S.; Santoso, A.D.; Ariningsih, E.; Widaningsih, N.; Hutahaean, L.; Priyanto, D.; Ilham, N.; Suharyon, S.; Herdis, H.; Widiawati, Y.; Hadiatry, M.C.; Ermuna, S.S.; Mardiharini, M.; Sugandi, D.; Bakrie, B.; Wasito, W., (2023). Analysing the sustainability of swamp buffalo (*Bubalus bubalis carabauesis*) farming as a protein source and germplasm. Open Agric., 8(1): 20220224 (**23 pages**).

Sadiku, M.N.O.; Adebo, P.O.; Majebi, A.A.; Musa, S.M., (2021). Sustainable agriculture. Int. J. Eng. Res. Technol., 10(9): 353-358 **(6 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages)**.

Samimi, M.; Mansouri, E., (2024). Efficiency evaluation of Falcaria vulgaris biomass in Co(II) uptake from aquatic environments: characteristics, kinetics and optimization of operational variables. Int. J. Phytoremediation, 1-11 **(11 pages)**.

Santoso, A.D.; Handayani, T.; Nugroho, R.A.; Yanuar, A.I.; Nadirah, N.; Widjaja, E.; Rohaeni, E.S.; Oktaufik, M.A.M.; Ayuningtyas, U.; Erlambang, Y.P.; Herdioso, R.; Rofiq, M.N.; Hutapea, R.; Sihombing, A.L.; Rustianto, B.; Susila, I.M.A.D.; Irawan, D.; Iskandar, D.; Indrijarso, S.; Widiarta, G.D., (2023b). Sustainability index analysis of the black soldier flies *(Hermetia illucens)* cultivation from food waste substrate. Global J. Environ. Sci. Manage., 9(4): 851-870 **(20 pages).**

Santoso, A.D.; Arianti, F.D.; Rohaeni, E.S.; Haryanto, B.; Pertiwi, M.; Panggabean, L.P.; Prabowo, A.; Sundari, S.; Wijayanti, S.P.; Djarot, I.N.; Kurniawati, F.; Sahwan, F.L.; Prasetyo, T.; Barkah, A.; Adibroto, T.A.; Ridlo, R.; Febijanto, I.; Wasil, A.A.; Lusiana, S.; Rosmeika, R., Heryanto, R. B., (2023). Sustainability index analysis of organic fertilizer production from paunch manure and rice straw waste. Global J. Environ. Sci. Manage., 9(SI): 193-218 (**26 pages**).

Santoso, A.D.; Hariyanti, J.; Pinardi, D.; Kusretuwardani; Widyastuti, N.; Djarot, I.N.; Handayani, T.; Sitomurni, I.; Apriyanto, H., (2023). Sustainability index analysis of microalgae cultivation from biorefinery palm oil mill effluent. Global J. Environ. Sci. Manage., 9(3): 559-576 **(18 pages).**

Saputro, K.E.A.; Hasim; Karlinasari, L.; Beik, I.S., (2023). Evaluation of Sustainable Rural Tourism Development with an Integrated Approach Using MDS and ANP Methods: Case Study in Ciamis, West Java, Indonesia. Sustainability. 15(3): 1835 **(9 pages).**

Setiawati, M.R.; Prayoga, M.K.; Stöber, S.; Adinata, K.; Simarmata, T., (2020). Performance of rice paddy varieties under various organic soil fertility strategies. Open Agric., 5(1): 509-515 (7 pages).

Sinha, D.; Tandon, P.K., (2020). Biological interventions towards management of essential elements in crop plants. Sustainable Solutions for Elemental Deficiency and Excess in Crop Plants. Springer.

Sivaraman, I.; Krishnan, M.; Radhakrishnan, K., (2019). Better management practices for sustainable small-scale shrimp farming. J. Cleaner Prod., 214: 559-572 (**14 pages**).

Sivakumar, D.; Srikanth, P.; Ramteke, P.W.; Nouri, J., (2022). Agricultural waste management generated by agro-based industries using biotechnology tools. Global J. Environ. Sci. Manage., 8(2): 281-296 **(16 pages).**

Suardi, T.F.; Sulistyowati, L.; Noor, T.I.; Setiawan, I., (2022). Analysis of the sustainability level of smallholder oil palm agribusiness in Labuhanbatu Regency, North Sumatra. Agriculture., 12(9): 1469 **(16 pages).**

Suhartini, S.; Rohma, N.A.; Elviliana; Santoso, I.; Paul, R.; Listiningrum, P.; Melville, L., (2022). Food waste to bioenergy: current status and role in future circular economies in Indonesia. Energy Ecol. Environ., 7(4): 297-339 **(43 pages).**

Sulistyono, N.B.E.; Wahyono, N.D.; Utami, M.M.D., (2019). Sustainability analysis of integrated farming business models of food crop and beef cattle. Proceeding of the 2nd International Conference on Food and Agriculture (ICOFA)., 2: 615–623 **(9 pages).**

Sumane, S.; Kunda, I.; Knickel, K.; Strauss, A.; Tisenkopfs, T.; Rios, I.D.L.; Rivera, M.; Chebach, T.; Ashkenazy, A., (2018). Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. J. Rural Stud., 59: 232-241 **(10 pages).**

Suradisastra, K., (2017). Sustainability of agricultural sector development: Technological innovation or institutional social innovation? Towards Modern Sustainable Agriculture. IAARD Press.

Surahman, A.; Soni, P.; Shivakoti, G.P., (2018). Are Are peatland farming systems sustainable? Case study on assessing existing farming systems in the peatland of Central Kalimantan, Indonesia. J. Integr. Environ. Sci., 15(1): 1-19 **(21 pages).**

Tanaka, D.L.; Krupinsky, J.M.; Liebig, M.A.; Merrill, S.D.; Ries, R.E.; Hendrickson, J.R.; Johnson, H.A.; Hanson, J.D., (2002). Dynamic cropping systems: An adaptable approach to crop production in the great plains. Agron. J., 94 (5): 957-961 **(5 pages).**

IAARD, (2011). General guidelines for Multi Channel Dissemination Spectrum. Spectrum Diseminasi Multi Channel. The Indonesian Agency for Agriculture Research and Development. Agriculture Ministry.

Tiong, J.S.M.; Chan, Y.J.; Lim, J.W.; Mohamad, M.; Ho, C.D.; Rahmah, A.U.; Kiatkittipong, W.; Wipoo, S.W.; Kumakiri,I., (2021). Simulation and optimization of anaerobic co-digestion of food waste with palm oil mill effluent for biogas production. Sustainability. 13(24): 13665 **(22 pages).**

Wadchasit, P.; Suksong, W.; O-Thong, S.; Nuithitikul, K., (2021). Development of a novel reactor for simultaneous production of biogas from oil-palm empty fruit bunches (EFB) and palm oil mill effluents (POME). J. Environ. Chem. Eng., 9(3): 105209 **(12 pages).**

Wan, C.; Shen, Q.S.; Choi, S., (2021). Underlying relationships between public urban green spaces and social cohesion: A systematic literature review. City Cult. Soc., 24: 100383 **(15 pages).**

Wedajo, D.Y.; Belissa, T.K.; Jilito, M.F., (2019). Harnessing indigenous social instutuions for technology adoption: Afoosha' society of Ethiopia. Dev. Stud. Res., 6(1): 152-162 **(11 pages).**

Wibowo, H.; Warna, R.N.; Wulandari, P.; Prakoso, T.; Prasetyo, D.; Airlangga, T.A.; Purwanto, B.H.; Utami, S.N.H.; Sulistyaningsih, E.; Handayani, S., (2019). Identification the availability of P in land planted with corn on volcanic, karst and acid soils in Indonesia. KnE Life Sci., 4(11): 179–188 (10 pages).

Widiati, W.; Mulyadi, A.; Syahza, A.; Mubarak., (2020). Analysis of plantation management achievement based on sustainable development. Int. J. Sustainable Dev. Plann., 15 (4): 575-584 **(10 pages).**

Wongnaa, C.A.; Mbroh, J.; Mabe, F.N.; Abokyi, E.; Debrah, R.; Dzaka, E.; Cobbinah, S.; Poku, F. A., (2023). Profitability and choice of commercially prepared feed and farmers' own prepared feed among poultry producers in Ghana. J. Agric. Food Res., 12: 100611 **(21 pages).**

Yang, G.; Li, J.; Liu, Z.; Zhang, Y.; Xu, X.; Zhang, H.; Xu, Y., (2022). Research trends in crop–livestock systems: a bibliometric review. Int. J. Environ. Res. Public Health. 19(14): 8563 **(13 pages).**

Yusuf, E.S.; Ariningsih, E.; Ashari, Gunawan, E.; Purba, H.J.; Suhartini, S.H.; Tarigan, H.; Syahyuti; Hestina, J.; Saputra, Y.H.; Wulandari, S.; Ilham, N.; Ariani, M., (2022). Sustainability of arabica coffee business in West Java, Indonesia: A multidimensional scaling approach. Open Agric., 7: 820–836 **(17 pages).**

Zhang, Y.; Ding, C., (2023). Using MDS preference plot as visual analytics of data: A machine learning approach. Methodol. Innovations. 16(1): 205979912211445 **(11 pages).**

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ORIGINAL RESEARCH PAPER

Evaluation of willingness to pay and challenges to community empowerment in urban drinkable water

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ABSTRACT

BACKGROUND AND OBJECTIVES: Environmental degradation, especially that related to water, has the potential to result in an unhealthy life. Humans drinkable water for basic needs, but poor water quality can cause disease. One of the solutions of households to obtain drinkable water is to subscribe to water companies. This study presents the notion of community engagement related to urban drinkable water supply, specifically by examining the willingness of community members to pay for such services in response to environmental pressures.

METHODS: This study used purposive sampling methods to determine the value of willingness to pay, identified challenges in the community through a questionnaire on drinkable water in Jakarta, Indonesia, and conducted estimation using ordinary least squares. This research used a sample of 503 households in Jakarta.

FINDINGS: The coefficient values of the control variables, namely, daily income (0.448), education level (4.344), and age (628.1), exhibited a positive correlation and statistically significant impact. Results indicate a positive and statistically significant association between the coefficient values of the variables of interest, namely, water quality (8.663) and water source (21.248), in willingness to pay for drinkable water. A one-unit increase in the coefficient score impacts the willingness to pay value, measured in Indonesian rupiahs. Findings indicate that the majority of the respondents expressed readiness to pay for drinkable water valued below 100,000 Indonesian rupiah per month, which is equivalent to under 6.30 United States Dollars. The suggested strategies for addressing the diverse issues encompass the necessity of implementing structural reforms involving the engagement of local leaders to enhance empowerment. This approach holds promise for effectively resolving the drinkable water crisis. Technical effort in shaping the behavior of urban communities in using and appreciating water is also essential to sustain the environment.

CONCLUSION: Environmental contamination issues have become a reason for households to subscribe to water companies. Customers are willing to pay to obtain clean and potable water. This study is essential as a basis for formulating policies that can be used by drinkable water companies regarding community members' ability to pay for water, preferences, and participation in protecting the environment.

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INTRODUCTION

Water is the most basic need for all living things on earth, including humans (Samimi *et al.,* 2023). Previous research shows that humans are indifferent to water use efficiency. Human activities have also been found to cause an increase in the burden of water pollution (Abidin, 2023; Kasim *et al.,* 2023; Samimi and Shahriari-Moghadam, 2023). Approximately 95 percent (%) of deadly illnesses are due to poor water quality (Olalekan *et al.,* 2019). Declining water quality in urban áreas, such as Jakarta, Indonesia, is affected by environmental factors because of decreased ecological functions and a lack of green open spaces (Mbarep and Herdiansyah, 2019). Jakarta is known as a metropolitan city because it has extremely diverse functions and roles. Households in Jakarta source clean water through tap water (8%), groundwater pumps (12%), and drinkable water companies (80%) (BPS, 2021a). Increased usage of water resources results in environmental concerns (Moghadam and Samimi, 2022). The 2019 Jakarta Resilience Secretariat Report indicates that 97.5% of reservoir water in Jakarta is polluted, 88% of river water is contaminated, and 68% of groundwater is polluted. The northern section of Jakarta is the worst-affected area because of the declining environmental condition, so water contaminated iron, sodium, chloride, and total dissolved solids (Fadly *et al.,* 2017). The groundwater quality evaluation in Jakarta in 2021 shows five dominant pollutant parameters, namely, potential hydrogen (pH), manganese, detergent, total coliform, and *Escherichia coli* (Dinas LH DKI Jakarta, 2021), which significantly affect the quality of life and the environment. Hence, healthy water means a healthy life. Improved standards must be developed to protect the environment. Several institutions, such as the Geology Agency, Jaya Regional Public Company for Drinkable Water/Perusahaan Umum Daerah Air Minum Jaya (PAM Jaya), and the Regional Government of Jakarta, collaborate to solve the related problems. Environmental and natural resource transformations entail an open-ended willingness to pay (WTP). PAM Jaya is a government public company supplying drinkable water to all areas in Jakarta with pay methods (Ismowati, 2018). The current study examines WTP of people in Jakarta for drinkable water sources by company. WTP is the amount of money people are prepared to pay in exchange for environmental resources (Tyllianakis and Skuras, 2016). WTP is a value reflecting consumers' assessment. Research on WTP for clean water in Jakarta by the government water company is fundamental in determining the best value for water. When WTP is known, it can be used as a benchmark by the regional and central governments to formulate policies related to the payment for clean water. The average WTP fee for improved drinkable water is about US Dollar (USD) 3.1 or 4.7% for two months or 0.22% per family in Mexico City (Rodríguez-Tapia, 2017), Indonesian Rupiah (IDR) 444,123.38 (USD 30) per month in Aceh Besar, Indonesia (Muazzinah *et al.,* 2020), 105,494.6 IDR (6.65 USD) in Katulampa Village, Indonesia (Syaukat and Maryani, 2020), and IDR 59,002 (USD 4.06) to IDR 132,652 (USD 9.13) per month in Cimahi, Indonesia (Prayoga *et al.,* 2021). The current research is slightly similar to previous research on WTP in Mexico, which used contingency valuation. However, the former was conducted in Jakarta using the ordinary least squares (OLS) method. Although research on WTP has been conducted in several regions in Indonesia, they differ from Jakarta. The current research focuses on drinkable water in urban areas because the environmental burden on capital cities reduces water quality. Hence, people tend to subscribe to drinkable water companies. No research has been comprehensively conducted involving household capacity for WTP and community engagement. Previous studies conducted in Vietnam have shown several major elements influencing water payment behavior, including gender, age, income, water usage patterns, payment methods, and maintenance practices (Bui *et al.,* 2022). Psychological variables have been observed to possibly play a role in shaping individuals' water payment behavior (Zolfagharipoor and Ahmadi, 2021). The determining factors used in previous research were age, education, income, family size, and gender in Aceh Besar, Indonesia (Muazzinah *et al.,* 2020) and Katulampa Village, Indonesia (Syaukat and Maryani, 2020). Some worldwide studies have focused on improving water quality (Lapworth *et al.,* 2020). In previous research on water pollution caused by oil spills, reaction readiness requires collaboration between corporations and communities, as well as increased understanding through community involvement (Soesilo *et al.,* 2020). Although several studies have been conducted on WTP factors related to drinkable water, there are still some unsolved issues, especially in capital cities. Geographical variances, demographic factors, and degrees of environmental pollution in urban water require specific research. The settlement concept proposed in this study involves urban community empowerment. Urban communities tend to have highly individualistic and socially restrained characteristics (Weckroth *et al.,* 2022). This study aims to obtain various WTP allocations from respondents regarding drinkable water use, analyze challenges in implementing WTP, and empower urban communities to make wise decisions regarding drinkable water use. Participation is in terms of community empowerment to satisfy them, manage water competently, and control the quality and quantity of water received from drinkable water companies. According to previous research, analyzing the development and distribution of water resources only through economic issues is not viable because economic and social goals may be discussed in a more complex manner (Hatamkhani and Moridi, 2021). The hypothesis proposes that daily income and water quality significantly impact the people of Jakarta's willingness to pay for drinkable water. Given that income is one of the essential factors in determining WTP in China, educational background has the most significant influence on WTP (Peng *et al.,* 2022). China used 419.2 cubic meters (m^3)/person/year in 2021 (National Bureau of Statistics of China, 2019). Resident of Jakarta used 31.11 m^3/household/month in 2021, obtained from the total volume of water sold divided by the number of household customers of PAM Jaya (BPS RI, 2023). These data show the difference in the amount of water each person uses in China and Jakarta. People seek the appropriate environmental services, and a higher service level objective will become more necessary. The most crucial aspects are finding solutions to obtain the best WTP for drinkable water and empowering communities for good water management behavior. Previous research has identified the relationship of WTP with environmental preferences (Hynes *et al.,* 2021), implementation of environment-friendly pharmaceutical policies (Alajärvi *et al.,* 2022), prevention of traffic-related air pollution (Istamto *et al.*, 2014), improvement of air quality (Rafique *et al.*, 2022), environment-friendly lifestyle behaviors (e.g., clothing, travel, housing, and waste recycling) (Geng *et al.,* 2023), and the desire to supply clean drinkable water (Cameron *et al.,* 2023). Previous research has also used sociodemographic characteristics on WTP. However, other factors, such as interest perspectives, should also be identified. The current research uses sociodemographic characteristics combined with an perspective on WTP. This study uses control variables (for sociodemographic characteristics) and variables of interest (perspectives on drinkable water). The present research is essential because it serves as a foundation for measures that drinkable water corporations may take regarding the community's willingness to pay for water, preferences, and community engagement in environmental protection. This research will also motivate the government to implement drinkable water policies. This study aims to evaluate WTP and the challenges of empowerment to address environmental issues for sustainable drinkable water in Jakarta from 2021 to 2022.

MATERIALS AND METHODS

The study was conducted through surveys using questionnaires and interviews with respondents as primary data. Secondary data were from PAM Jaya. This research uses a questionnaire combining open, closed, and Likert scale answers (Table 1). Variables using open answers are daily income (in IDR/day), education level (in years), respondents' age (in years), and total water consumption expenditure (in IDR/month). Closed questions were on marital status (e.g., married), gender (e.g., male or female), and primary water source (e.g., regional companies or groundwater). The Likert question is on the primary water source quality variable with the following point range: 5 (very good), 4 (good), 3 (neutral), 2 (por), and 1 (very por). The satisfaction level variable also uses a Likert scale with the following point range: 5 (very satisfied), 4 (satisfied), 3 (neutral), 2 (dissatisfied), and 1 (very dissatisfied). The survey was conducted in Jakarta (Fig. 1), with the overall theme of Jakarta Clean Water Survey in 2021. Consideration for choosing a location is based on the complexity of the environmental problems in Jakarta, including the clean water crisis. BPS RI (2021b) indicates that the number of households in Jakarta is 2,770,729. The study sample size is 503 households. Jakarta is between 6 degrees (°) 8 minutes (') South (S) and 106°48' East (E). Jakarta borders Banten Province to the west, West Java Province to the south, and

Table 1: The Questionnaire

List of Questions	Answer
Variables of control	
Income per day	IDR / day
Education Level	Elementary; Junior high school; senior high school; university; none
Age	In year
Marital Status	1 = Married; 0 = else
Gender	1 = Male; 0 = Female
Variable of interests	
What do you think about the quality of water?	1 = very poor; 2 = poor; 3 = neutral; 4 = good; 5 = very good
How much is the total expenditure on water consumption? (in IDR/month)	(respondents will answer the cost of water expenditures)
Where do you get your main water source?	1 = local government company; 0 = ground water
What is the satisfaction level of the water source?	1 = very dissatisfied; 2 = dissatisfied; 3 = neutral; 4 = satisfied; 5 = very satisfied

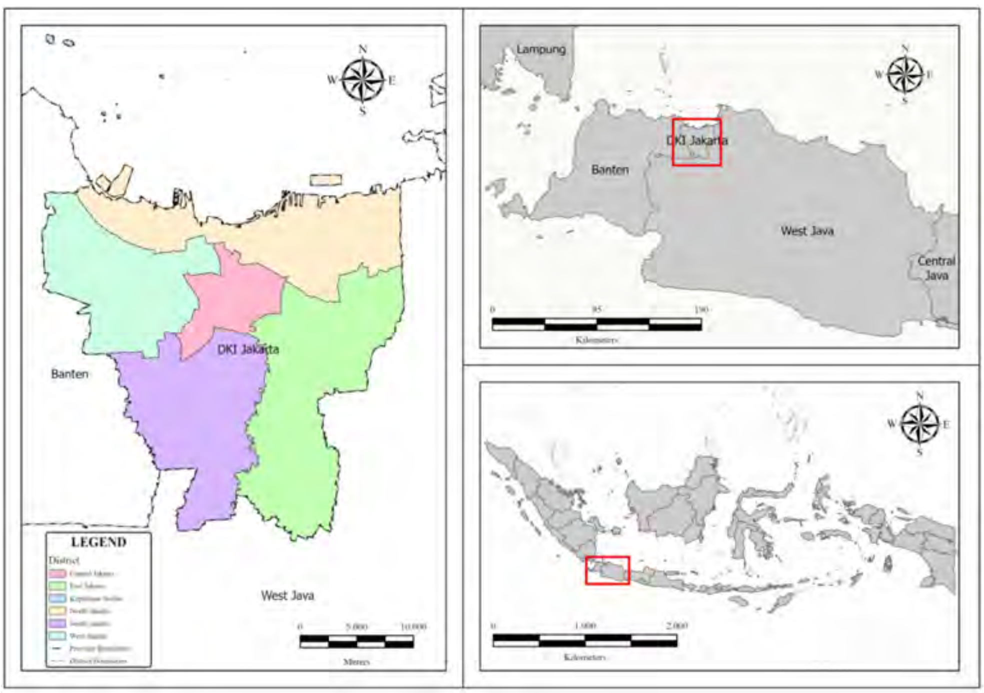

Fig. 1: Geographic location of the study area in Jakarta, Indonesia

Java Sea to the north (BPK RI., 2023). Jakarta has a total administrative area of 662.3 square kilometers (km^2). Jakarta has an average air temperature of 28.5 degrees Celcius (°C), with a maximum air temperature during the day ranging from 33.8 °C to 35.2 °C. Jakarta's minimum air temperature at night is from 23 °C to 24.6 °C. Lastly, Jakarta has an average rainfall throughout the year of 237.96 millimeters (mm) (DISKOMINFOTIK Pemprov. DKI Jakarta., 2023).

This study investigates the willingness of people to pay for drinkable water because of environmental preferences. This study uses the OLS approach to determine how socioeconomic and water-related variables influence respondents' WTP for drinkable water. OLS is a linear regression approach to estimate unknown parameters in a model with a fixed effect of a collection of explanatory variables. Normality, multicollinearity, heteroscedasticity, and autocorrelation tests determine if the predicted coefficients are correct. Gujarati and Porter (2009) stated that estimated coefficients in the OLS model must meet three criteria. First, the coefficient estimate must be linear, which means that the OLS estimate is a linear function of a random variable (e.g., independent variable in a regression model). Second, the estimated coefficient is unbiased, which means that the average value or prediction of the estimator is as close as possible to the actual value. Lastly, the estimated coefficients must be efficient, which means that the OLS estimator has a low variance to guarantee efficiency. OLS is one of the simplest methods to determine the significant variable affecting WTP through linear regression (Kavosi *et al.,* 2018). The OLS method seeks to accurately approximate a mathematical function to a given data set. This method achieves this objective by minimizing the sum of squared errors derived from the data set. The dependent variable is WTP for drinkable water. The control factors comprise income, education, age, marital status, and gender. The variables under consideration are the quality of the primary water source, total water consumption expenditure, a binary variable indicating the type of water source, and level of satisfaction with the primary water source, as shown in Eq. 1 (Gujarati and Porter, 2009).

$$\text{WTP of drinkable water} = \beta_0 + \beta_1 X1 + \beta_2 X2 + \beta_3 X3 + \beta_4 X4 + \beta_5 X5 + \beta_6 X6 + \beta_7 X7 + \beta_8 X8 + \beta_9 X9 \quad (1)$$

Where;

β_0 = Intercept

$\beta_1 - \beta_9$ = Coefficient parameter of the independent variable

$X1$ = Income per day

$X2$ = Education Level

$X3$ = Respondents' age

$X4$ = Dummy variable of marital status

$X5$ = Dummy variable of gender

$X6$ = Quality of main water source (scores of 1 until (–) 5)

$X7$ = Total water consumption expenditure

$X8$ = Dummy of the main water source (1 = local government company; 0 = ground water)

$X9$ = Satisfaction level on current primary water source (scores of 1–5)

WTP of the drinkable water variable is the respondents' material valuation from a specific total budget. The conversion of IDR to USD on October 30, 2023 at 09:00 Universal Time Coordinated (UTC) is USD 1 USD = IDR 15,878.75. In this survey, respondents were asked to spend IDR 1 million (USD 63) on several clean water aspects (the WTP variable is in IDR). Likert scale and quantitative analysis were conducted to assess the respondents' perspectives on the effect of WTP in drinkable water. A quantitative study was conducted to determine the expenditure allocation of respondents who buy drinkable water. Data analysis was performed using Microsoft Excel 2010 and Statistical Package for the Social Science (SPSS) 25.0.

RESULTS AND DISCUSSION

This study has five control variables, reflecting the respondents' socioeconomic factors, and four variables of interest in Jakarta. Owing to population density in metropolitan areas, there is a detrimental environmental impact on the surrounding region. The five control variables can determine WTP for clean water in Jakarta. Data analysis output has five estimation models (est), as shown in Eqs. 2 to 6 (Gujarati and Porter, 2009).

$$\textbf{Model}1: -35,723 + 0.453\mathbf{X}1 + 3,366\mathbf{X}2 + 620.6\mathbf{X}3 + 14,626\mathbf{X}4 - 5,808\mathbf{X}5 \quad (2)$$

$$\text{Model}2: -76,414 + 0.459X1 + 3,812X2 + 628.1X3 + 14,293X4 - 4,271X5 + 7,164X6 \quad (3)$$

$$\text{Model}3: -76,354 + 0.457X1 + 3,807X2 + 628.1X3 + 14,282X5 - 4,306X5 + 7,171X6 + 0.00193X7 \quad (4)$$

$$\text{Model}4: -63,358 + 0.447X1 + 4,193X2 + 377.7X3 + 14,149X5 - 7,708X5 + 8,663X6 + 0.00514X7 - 20,777X8 \quad (5)$$

$$\text{Model}5: -82,188 + 0.448X1 + 4,344X2 + 388.9X3 + 14,843X5 - 7,244X5 + 5,820X6 + 0.0065X7 - 1,248X8 + 6,177X9 \quad (6)$$

Numbers enclosed in parentheses represent the standard error of estimation (SEE), which estimates the coefficient's standard deviation (Table 2). The coefficient is the number not enclosed in parentheses. The coefficient calculates the predicted change in the dependent variable due to the control variable (est1);

Table 2: Regression results of WTP in five controlling variables, reflecting respondents' socioeconomic factors and four variables of interest

Variables	Probability for WTP for drinkable water				
	Est1	Est2	Est3	Est4	Est5
Variabel of control					
Income per day	0.453***	0.459***	0.457***	0.447***	0.448***
	(0.0389)	(0.0391)	(0.0416)	(0.0413)	(0.0413)
Education level	3,366	3,812	3,807	4,193*	4,344*
	(2,541)	(2,557)	(2,561)	(2,537)	(2,542)
Age	620.6**	628.1**	628.1**	377.7	388.9
	(304.0)	(303.7)	(304.0)	(310.0)	(310.2)
Marital status (1 = married; 0 = else)	14,626	14,293	14,282	14,149	14,843
	(9,645)	(9,638)	(9,649)	(9,549)	(9,578)
Gender (1 = male; 0 = female)	-5,808	-4,271	-4,306	-7,708	-7,244
	(11,500)	(11,538)	(11,557)	(11,482)	(11,494)
Variable of Interests					
Quality of water		7,164	7,171	8,663*	5,820
		(5,009)	(5,015)	(4,983)	(5,806)
Expenditure for water consumption			0.00193	0.00514	0.00650
			(0.0222)	(0.0220)	(0.0221)
Main water source (1 = water from company; 0 = ground water)				-20,777***	-21,248***
				(6,169)	(6,189)
Satisfaction level on current water source					6,177
					(6,471)
Constant	-35,723	-76,414*	-76,354*	-63,358	-82,188*
	(34,285)	(44,525)	(44,575)	(44,285)	(48,483)
R-squared	0.234	0.237	0.237	0.254	0.255

Notes: *= Probability value (p-value) less than (<) 0.1; **=p-value<0.05; ***=p-value<0.01; the coefficient of regression is the number that is not in parentheses; the number inside the parentheses indicates SEE

control variable and quality of primary water source (est2); control variable, quality of primary water source, and expenditure for water consumption (est3); control variable, rate of primary water source, expenditure for water consumption, and direct water source (est4); and control variable and variable of interest (est5). The regression result in Table 2 indicates five estimates of the model. The model shows an coefficient of determination (R-squared) value from 0.234 (est1) to 0.255 (est5). Note that model 5 has the highest R-squared value of 25.5% in WTP for drinkable water, which has been explained by various variables in the study. By contrast, the remaining 74.5% is explained by other variables not included in the regression model equation. Hence, model 5 was chosen as the primary model for the analysis. Daily income significantly influences WTP for drinkable water in all estimations. In est5, an income increase of IDR 1,000 (USD 0.063) will increase WTP to IDR 448 (multiplied by 1,000 for a more straightforward interpretation). In est4 and est5, an increase in education by one year tends to significantly increase WTP to IDR 4,344 (USD 0.27). This finding indicates that citizens with higher education levels increases WTP value to IDR 2,542 (USD 0.16) compared with citizens with low/less education. These findings align with previous research that WTP increases with income and education, thereby ensuring drinkable water quality (Jianjun *et al.,* 2016). Analysis of the age variable shows that est1, est2, and est3 have a positive and significant effect on WTP. Thus, an increase in age by 1 year will increase WTP to IDR 628.1 (USD 0.04). This result aligns with previous research, in which WTP for clean water consumed is influenced by age (Rananga and Gumbo, 2015). The first variable of interest is the quality of the primary water source. According to Table 2, citizens' direct water source quality positively correlates with WTP for drinkable water. Consequently, an increase in home water quality by 1 level will increase WTP for drinkable water to IDR 8,663 (USD 0.55 USD) (est4). Citizens who are subscribers of public water services tend to have lower WTP for drinkable water by IDR 21,248 (USD 1.34) compared with respondents using groundwater. The following variable of interest is the satisfaction level, which has a positive but insignificant impact on WTP for drinkable water. On the basis of est5, an increase in satisfaction by 1 level will increase WTP by IDR 6,177 (USD 0.39). This study conducted a graphical analysis through figures to further understand the significance of the variable to strengthen the OLS model.

Graphical testing is needed to assess the significance variable based on Table 2. Graphical testing results are presented Fig. 2, Fig. 3, and Fig. 4. The trend with a linear slope is shown in Fig. 2. That is, the income variable significantly influences WTP decisions. Higher household income significantly affects the respondents' WTP for safe drinkable water (Chatterjee *et al.,* 2017). Fig 2. shows a positive relationship, indicating that citizens' WTP will increase as their income increases. The finding confirms the hedonic consumption theorem, in which spending increases as income increases (assuming that drinkable water is an everyday resource). The linear regression data distribution indicates that most respondents choose the WTP for monthly drinkable water under IDR 100,000 (USD 6.30). The research findings show that the higher a person's income, the higher the WTP. That is, people with low incomes have difficulty making payments. Accordingly, this research found a WTP value based on the agreement of the majority of the respondents. The DKI Jakarta government must immediately overcome this phenomenon. A posible solution is to optimize subsidies for low-income people. The following control variable is education

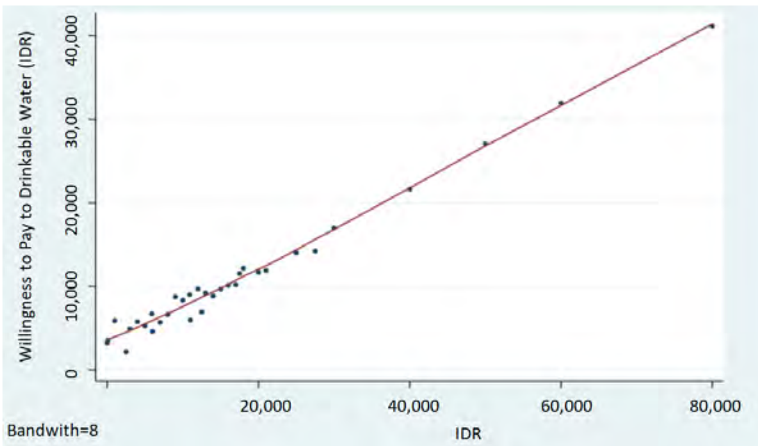

Fig 2: Control variables of income per day

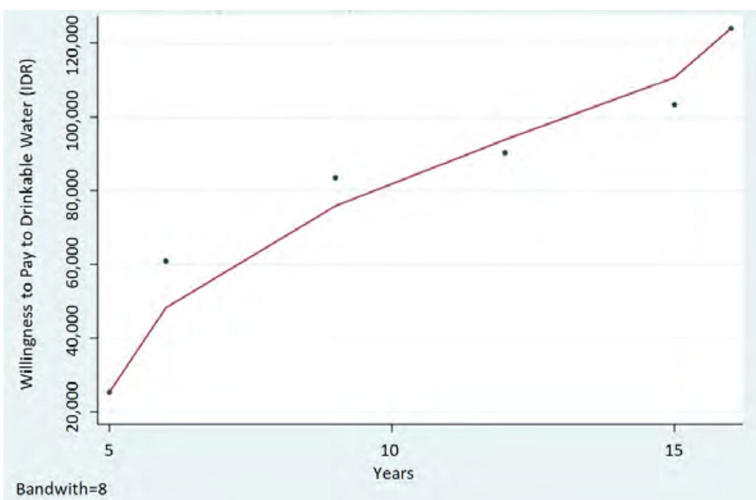

Fig. 3: Control variables of education level

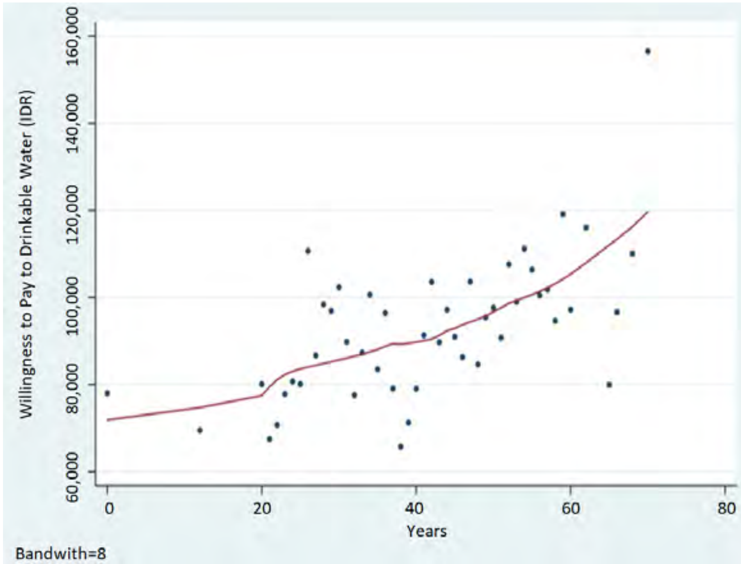

Fig. 4: Control variables of age

level (Fig. 3). The study results show that the higher a person's education, the higher the WTP for drinkable water. Analysis shows that the slope of WTP increase is weakly positive. That is, the increase rate of WTP is lower than the increase in age (Fig. 4). Older people know more about the consequences if they do not pay for clean water.

As shown in Fig. 5, water quality has a fluctuating relationship with WTP for drinkable water. When water quality is excellent (score: 5), WTP decreases to between IDR 80,000 (USD 5.04) and IDR 90,000 (USD 5.67 USD). There appears to be an optimal level of WTP for drinkable water (score: 4), in which citizens will value it highly to pay environmental guarantees to ensure clean water. Water contamination occasionally occurs owing to regional ecological environment degradation (Aregay *et al.,* 2016). Hence, quality of drinkable water is influenced by environmental degradation in Indonesia, which occurs owing to mining operations (Meutia *et al.,* 2023), domestic waste activities, industry, and uncontrolled agricultural activities (Sulthonuddin *et al.,* 2018). The Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017 concerning Environmental Health Quality Standards and Health Requirements for Water for Hygiene, Sanitation, Swimming Pools, Aqua Solutions, and Public Baths (Peraturan Menteri Kesehatan Republik Indonesia Nomor 32 Tahun 2017 Tentang Standar Baku Mutu Kesehatan Lingkungan dan Persyaratan Kesehatan Air untuk Keperluan Higiene Sanitasi, Kolam Renang, Solus Per Aqua, dan Pemandian Umum) explains that the use of water for sanitary hygiene purposes must meet environmental health quality standards in the form of physical, biological, and chemical parameters. The physical parameters that must be met are turbidity, with a maximum quality standard of 25 nephelometric turbidity unit (NTU), maximum color of 50 true color unit (TCU), maximum dissolved solids of 1000 milligrams per liter (mg/l), maximum air temperature of plus or minus (±) 3 °C, tasteless, and odorless. Biological parameters that must also be met are the presence of total coliforms of a maximum of 50 colony forming units (CFU)/100 milliliters (ml) and the complete absence of *Escherichia coli*. Lastly, the chemical parameters that must be met are to have a maximum pH of 6.5–8.5 mg/l, maximum of 1 mg/l iron, maximum of 1.5 mg/l fluoride, maximum hardness of 500 mg/l, maximum of 0.5 mg/l manganese, máximum of 10 mg/l nitrate (as N), máximum of 1 mg/l nitrite (as N), maximum 0.1 mg/l cyanide maximum, máximum of 0.05 mg/l detergent, and máximum of 0.1 mg/l pesticide. Providing water parameters for sanitation hygiene aims to ensure safe water use for personal hygiene (e.g., brushing teeth and bathing) and household needs

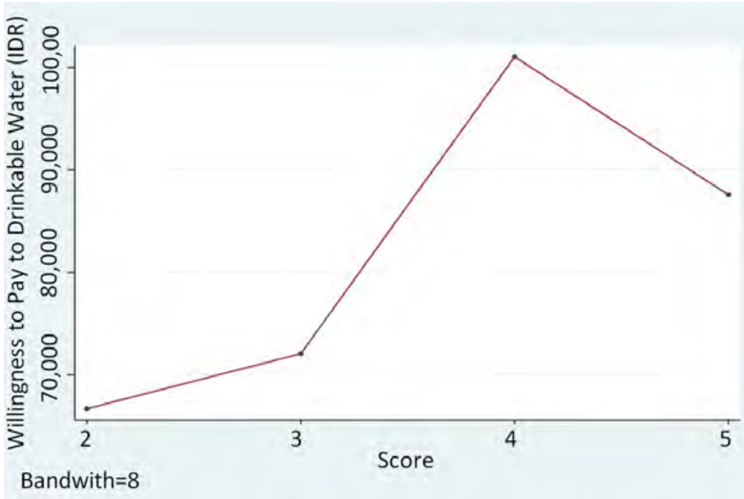

Fig. 5: Impact of water quality

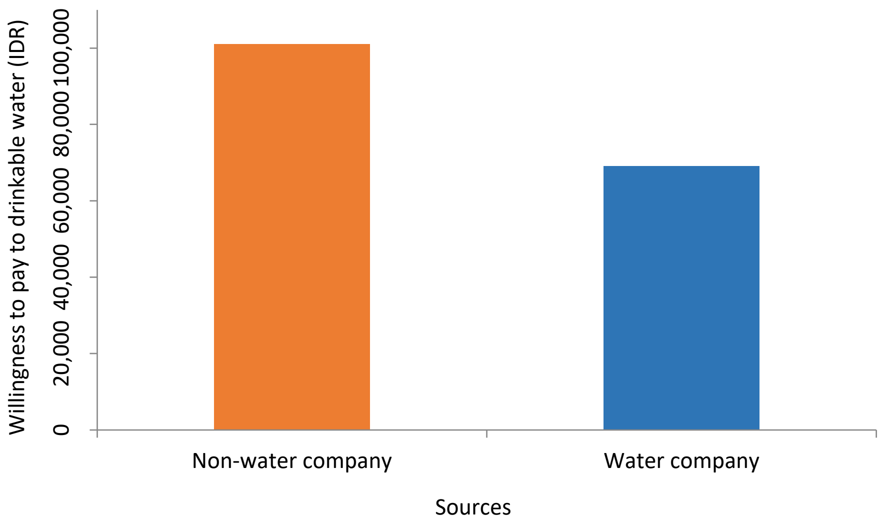

Fig. 6: WTP by main water sources

(e.g., washing cooking ingredients, eating utensils, and clothing). The regulation also states that water from sanitation hygiene can be used as raw drinkable water (Pemerintah Indonesia, 2017). As shown in Fig. 6, subscribers of public water services have lower WTP for drinkable water compared with groundwater users. That is, the cost of non-subscriber water companies is higher for non-public water companies owing to the higher maintenance of tools, electricity, and treatment. Water quality provided by public water companies is superior to groundwater managed on a large scale. Water companies work with technology. The customer perspective shows concern for the physical environment, with the majority agreeing to choose water companies because they ensure quality. Water companies often share information on their physical environment (Moore *et al.,* 2023). Given that subscribers already pay for the utility service, their WTP is lower. However, groundwater consumers have higher WTP because they do not pay for the utility service and expect higher water quality for environmental protection. The public's desire to buy water can be mitigated by establishing regulations, such as implementing cross-subsidies

Table 3: Expenditures of water supply establishment 2021 in Jakarta by water company (BPS RI., 2023)

Type of expenditure	Total (million IDR)	Total (million USD)
Employee compensation	505,483	31,83
Cost of chemical	39,004	2.46
Cost of operational	616,635	0.039
Cost of recovery and environmental management	0	0
Cost of fuel and lubricant	3,228	0.21
Cost of electricity	177,405	11.17
Another cost	637,104	43.12

between developing districts, which is the most efficient policy instrument. Efficient and sustainable water pricing should be based on a thorough understanding of consumer preferences related to their attitudes toward the costs of water supply security. Analysis of consumer WTP to improve water supply security (WSS) is required by policy makers and other authorities responsible for improving WSS (Wang *et al.,* 2018).

Influence of the living habits of Jakarta's citizens on WTP for drinkable water

The analysis of the control and interest variables indicates that most people are "willing and able" in terms of the WTP value for drinkable water below IDR 100,000 (USD 6.30 USD). This result is shown in the data distribution in the regression is Figs. 1 and 2. Only a few respondents chose to pay over IDR 100,000 (over USD 6.30) owing to high income and the high need for water for business or the number of family members. The WTP value is paid to drinkable water distribution companies in the hope that respondents will receive the appropriate quantity and quality of water. Drinkable water distribution companies also provide data on WTP allocations from all customers for water supply establishments. These companies present all costs to consumers (including operational and environmental costs). As shown in Table 3, expenditures are highest in the other cost categories, requiring a markedly detailed explanation of the budget allocation. The opinion of DKI Jakarta residents on PAM Jaya still needs to be considerably optimal in providing a clean water supply to all citizens of Jakarta (Hermawan and Hananto, 2022). The suitability of the quantity and quality customers receive must be evaluated to equalize perceptions and quantity and quality improvement. The total cost of infrastructure renewal and upkeep are components relating to the cost of environmental conservation to ensure that water is well distributed. The respondents' assessment as consumers of the purchase and selling prices of companies must be discussed further. The most crucial aspect is to improve and monitor the environment around the company's water resources (Khan *et al.,* 2019). Risk management and risk efficiency indicated that the mechanism for meeting the needs of clean water in Indonesia, namely public–private partnerships, is one of the most influential and sustainable, with 43.8% of the allocated risk being transferred from the government to the project company, and 25% becoming shared risk (Wardhana, 2020). There are government regulations on the classification of clean water customer groups based on the Second Amendment of the Governor of Jakarta Province to Governor Regulation Number 11 of 2007 concerning Automatic Drinkable Water Tariff Adjustments for Semester 1 of 2007. These regulations indicate that the classification of water use (0–3 m^3, >3–10 m^3, >10–20 m^3, and >20 m^3) is further grouped by cost. In Jakarta, it is 31.11 m^3/household/month in 2021 (data obtained from the total volume of water sold divided by the number of household customers from PAM Jaya) (BPS RI., 2023) with expenditure from IDR 32,666 (USD 2.06) to IDR 304,878 (USD 19.21). This finding is consistent with the study findings in Fig. 3. That is, public spending is below IDR 200,000 (USD 12.60), but some consumers in this study are WTP over IDR 200,000 (USD 12.60). Compared with drinkable water bottles, the price per large pack (19 liters) is about IDR 20,000 (USD 1.26). If one household consumes 31.11 m^3/household/month, then households have to spend IDR 32,747,368 (USD 2,062.34). On the bases of these data, drinkable water from PAM Jaya is a significantly better and have lower price than drinkable bottles for households in

Jakarta. The cluster of customers is not plotted based on the household's primary income. Stakeholders must consider income factors to cluster customer groups in drinkable water distribution.

Empowerment of urban community in water management

An analysis of indicators of the largest pollutant sources for Jakarta's groundwater quality indicates that domestic (household) waste activities are supported by hydrogeological conditions and soil characteristics in each region (Dinas LH DKI Jakarta, 2021). Environmental issues of water pollution in groundwater (Fadly *et al.,* 2017), surface water lakes, rivers, and oceans have a high risk of pollution. The previous study shows that most respondents choose drinkable companies, but challenges arise on how much value water for WTP has been released because of diversity in the community. The challenges refer to the ability to pay and use water wisely or not by consumers. Previous research has suggested that subsidies in Jakarta through the cross-subsidy mechanism enable water consumers in high-water consumption families to pay less than they should, which does not stimulate water-saving behavior (Suratin *et al.,* 2019). The relationship between service quality dimensions with customer satisfaction and WTP shows that responsiveness, reliability, and tangible significantly affect customer satisfaction but only up to level 4 satisfaction. Customer satisfaction will increase customer loyalty to service providers. Eventually, customer loyalty and satisfaction will significantly increase WTP (Haumann *et al.,* 2014). The study shows that satisfaction with services, such as clean water sources provided by PAM Jaya, will enhance customers' desire to pay for the services of PAM Jaya. Customer satisfaction has emerged as a critical component of company strategy. Many businesses have developed systems for monitoring and improving customer service (Koschate and Hoyer, 2013). Reviewing consumer behavior in managing drinkable water is crucial. A challenging aspect is to assist consumers in connecting water consumption to the environment. Promoting education on wise water usage through various means is essential to make communities aware of environmental justice. Massive education effort can be exerted by disseminating digital content (Sá *et al.,* 2023) and incorporating water management topics into the school curriculum (Amahmid *et al.,* 2018). The reason is that education will lead to improved water-conservation behavior (Xiong *et al.,* 2016). Digital solutions fostering social awareness should be integrated into sustainable urban water management and infrastructure development (Sá *et al.,* 2023). Another essential factor is to acknowledge the limitations of digital education, given that Internet access may be restricted for specific individuals. Community empowerment for water education should be continuous to change the behavior to respect the environment. Society should evolve to conserve rivers and their surroundings (Hynes *et al.,* 2021). All parties must be responsible for this conservation because the populace has established a practice of discarding rubbish into river streams (Nurwahdah *et al.,* 2023). Serious effort must be exerted to overcome water pollution, including increasing community participation by improving upstream land cover and water absorption in urban areas (Abidin, 2023). Technical effort in modifying the behavior of urban residents to consume, appreciate, and utilize water is also required to integrate mitigation and sustainability in the empowerment element. Society's empowerment can be achieved through influential figures within small clusters in the surrounding environment who provide examples and recommendations for water management practices, such as utilizing sensor-equipped faucets. Using sensor-based taps can be highly beneficial (Salehi *et al.,* 2020) in cases where water users forget to turn off the faucet or develop Internet of Things (IoT) (Tasong and Abao, 2019). Although the philosophy of the hydrological cycle guarantees water availability, monitoring significant climate change and implementing technical water management measures is crucial. In urban environments, rainwater harvesting (Campisano *et al.,* 2017) can be employed with installations on rooftops (Johnson *et al.,* 2022), as well as utilizing recycled water through a loop system (Casazza *et al.,* 2021). The quality and quantity of wáter must be recognized. As shown in Fig. 7, public awareness of purchasing drinkable water is caused by income per day, education level, age, quality of water, and main water source. Purchasing drinkable water must start with increasing public knowledge of the importance of providing quality drinkable water that does not endanger health. Increasing knowledge can be done through health communication strategies using various media that can reach the public,

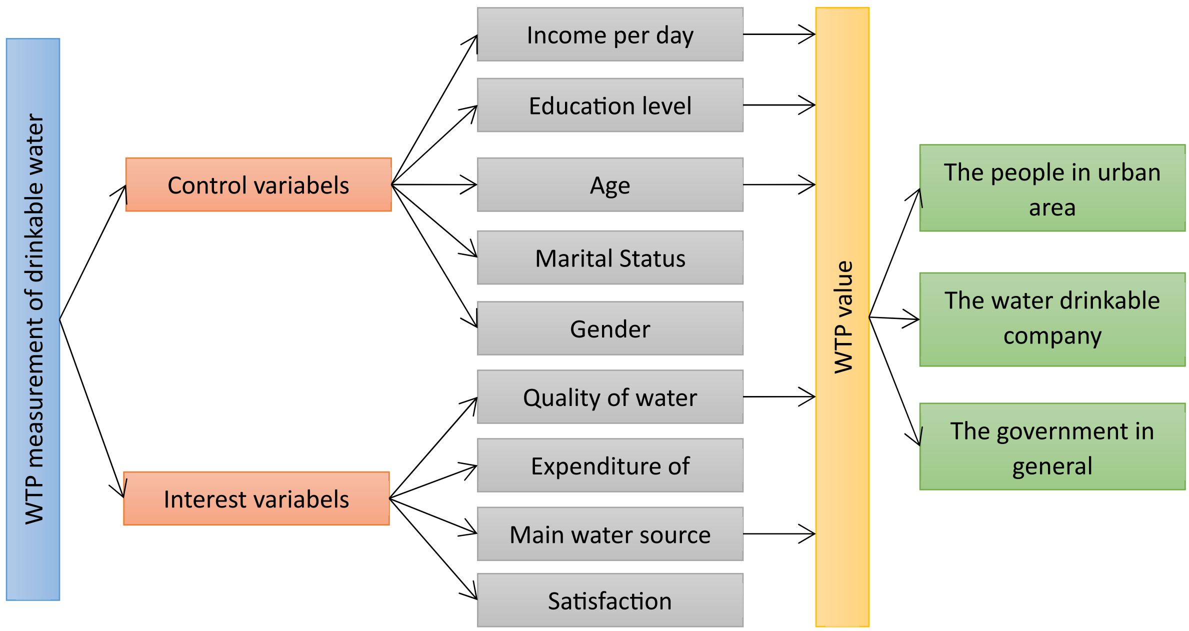

Fig. 7: Implications of WTP for urban planning

including social media, mass media, and other telecommunications media. Environmental health officers in community health centers can also work with health promotion officers to reach communities directly and enable exposure to information. A multi-sector approach, involving the government, state-owned companies, and the private sector, also plays an essential role. The government can participate in licensing the establishment of drinkable water supply businesses accompanied by periodic monitoring and evaluation by regulations. The private sector and state-owned companies can ensure affordable access to drinkable water that meets standards, thereby reducing barriers, including time and distance, which may prevent people from purchase drinkable water. Companies must also guarantee customer rights and carry out their responsibilities as indicated in the Minister of Health Regulation, Indonesia number 492/MENKES/PER/IV/2010, stating that every drinkable water operator must guarantee that the results of its production are safe for health (Pemerintah Indonesia, 2010).

CONCLUSION

Assessment of WTP for drinkable water in Jakarta considered five control variables, reflecting the respondents' socioeconomic factors and four variables of interest. The control variables include income, education, age, marital status, and gender. The four variables of interest are the quality of the leading water source, total expenditure for water consumption, dummy variable representing the water source, and current satisfaction level with the existing primary water source. The coefficient values of the control variables, namely, daily income (0.448), education level (4.344), and age (628.1), exhibit a positive correlation and a statistically significant impact. The results indicate a positive and statistically significant association between the coefficient values of the variables of interest, namely, quality of water (8.663) and main water source (21.248), in WTP for drinkable water. The highest R-squared value of 25.5% in WTP for drinkable water has been explained by various variables in the study. By contrast, the remaining 74.5% is explained by other variables not included in the regression model equation. Model 5 was chosen as the primary model for the analysis. Daily income will increase WTP to IDR 448 (multiplied by 1,000 for a more straightforward interpretation), education will increase to IDR 4,344 (USD 0.27), education levels will increase WTP value to IDR 2,542 (USD 0.16) compared with citizens with low/less education, the age variable will increase WTP to IDR 628.1 (USD 0.04), and water quality will increase WTP to IDR 8,663 (USD 0.55). Citizens who are subscribers of public water services tend to have lower WTP of drinkable water by IDR 21,248 (USD 1.34) than respondents with groundwater. The discussions indicate that the drinkable WTP most often chosen by the public is below IDR 100,000 (below USD 6.30) per month, and the interest variable on the water source quality factor shows the same thing. The preceding description illustrates that challenges and problems can arise from companies as drinkable water providers and the community as consumers. Community empowerment programs should educate and shift the paradigm that the availability of clean drinkable water is only occasionally guaranteed without interruption. Consequently, the implications of this research to build a framework for companies and governments are that various factors influence WTP decisions and abilities. However, the most logical decision is when they are willing to subscribe to water companies because environmental pollution in water is high risk for health. This study's novelty significantly contributes to determining WTP for citizens of DKI Jakarta, PAM Jaya in particular, and the government in general because every province in Indonesia has its own regional drinkable water Company. In addition, local governments manage these companies in collaboration with the central government. This finding indicates that the policy issue of targeting must be considered. Drinkable water can be accessed in communities through cross-subsidies. Another policy is WTP for drinkable water with a cluster system based on the control variable of income per day (level significance of 99%) to make WTP affordable for people in urban areas.

AUTHOR CONTRIBUTIONS

H.A. Negoro participated in methodology, validation, software, formal analysis, and preparing pictures and tables of study results. N.I.D. Arista participated in writing the original draft, reviewing and editing, and preparing pictures and tables of study results. D.E. Purba was the corresponding author, supervising the study, writing—review and editing, obtaining funding, and conceptualization.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

°	Degrees
°C	Degrees Celsius
ʻ	Minutes
–	Until
%	Percent
β_0	Intercept
$\beta_1 - \beta_9$	The coefficient parameter of the independent variable

<	Less than
±	Plus or minus
BPS RI	Badan Pusat Statistika Republik Indonesia (Central Statistics Agency of the Republic of Indonesia)
CFU	Colony Forming Units
Dinas LH DKI Jakarta	Dinas Lingkungan Hidup Daerah Khusus Ibukota Jakarat (Special Regional Environmental Service for the Capital City of Jakarta)
E	East
Est	Estimation model
Fig.	Figure
IDR	Indonesian rupiah
IoT	Internet of Things
km^2	Square kilometers
m^3	Volume (cubic meters)
mg/l	Milligrams per liter
ml	Milliliters
mm	Millimeters
NTU	Nephelometric Turbidity Unit
OLS	Ordinary least squares
PAM Jaya	Perusahaan Umum Daerah Air Minum Jaya (Jaya Regional Public Company for Drinkable Water)
p-value	Probability value
pH	Potential of hydrogen
R-squared	Coefficient of determination
S	South
SEE	Standard error of estimate
SPSS	Statistical package for the social science
TCU	True Color Unit
USD	United States dollar
UTC	Universal Time Coordinated
WSS	Water Supply Security
WTP	Willingness to Pay
$X1 - X9$	Variables

REFERENCES

Abidin, J.Z., (2023). Challenges in dealing with water pollution issues in the West Java island. J. Sustain. Society Eco-Welf., 1(1): 31–48 **(18 pages)**.

Alajärvi, L.; Lehtimäki, A.V.; Timonen, J.; Martikainen, J., (2022). Willingness to pay for implementation of an environmentally friendly pharmaceutical policy in Finland-a discrete choice experiment study. Int. J. Environ. Res. Public Health, 19(11): 6535 **(13 pages)**.

Amahmid, O.; El Guamri, Y.; Yazidi, M.; Razoki, B.; Kaid, R.K.; Rakibi, Y.; Knini, G.; El Ouardi, T., (2018). Water education in school curricula: Impact on children knowledge, attitudes and behaviours towards water use. Int. Res. Geogr. Environ. Educ., 28(3): 178–193 **(16 pages)**.

Aregay, F.A.; Zhao, M.; Li, X.; Xia, X.; Chen, H., (2016). The local residents' concerns about environmental issues in Northwest China. Sustainability, 8: 226 **(10 pages)**.

Bui, N.T.; Darby, S.; Vu, T.Q.; Mercado, J.M.R.; Bui, T.T.P.; Kantamaneni, K.; Nguyen, T.T.H.; Truong, T.N.; Hoang, H.T.; Bui, D.D.; Franchini, M.; Bui, N.T.; Darby, S.; Vu, T.Q.; Margaret, J.; Mercado, R.; Thi, T.; Bui, P.; Kantamaneni, K.; Nguyen, T.H.; Truong, T.N.; Hoang, H.T.; Du, B.D., (2022). Willingness to pay for improved urban domestic water supply system: the case of Hanoi, Vietnam. Water, 14(4): 2161 **(24 pages)**.

Cameron, D.B.; Ray, I.; Parida, M.; Dow, W.H., (2023). Product preferences and willingness to pay for potable water delivery: Experimental evidence from rural Bihar, India. PLoS One, 18(4): e0283892 **(27 pages)**.

Campisano, A.; Butler, D.; Ward, S.; Burns, M.J.; Friedler, E.; DeBusk, K.; Fisher-Jeffes, L.N.; Ghisi, E.; Rahman, A.; Furumai, H.; Han, M., (2017). Urban rainwater harvesting systems: Research, implementation and future perspectives. Water Res., 115: 195–209 **(14 pages)**.

Casazza, M.; Xue, J.; Du, S.; Liu, G.; Ulgiati, S., (2021). Simulations of scenarios for urban household water and energy consumption. PLoS One. 16(4): e0249781 **(15 pages)**.

BPK RI, (2023). Pemerintah Provinsi DKI Jakarta.

BPS RI, (2021a). Distribusi Persentase Rumah-Tangga Menurut Kabupaten Kota Dan Sumber Air Minum Di Provinsi DKI Jakarta.

BPS RI, (2021b). Jumlah Rumah Tangga Menurut Kabupaten Kota di Provinsi Jakarta.

BPS RI, (2023). Statistik Air Bersih Jakarta 2019-2021.

Chatterjee, C.; Triplett, R.; Johnson, C.K.; Ahmed, P., (2017). Willingness to pay for safe drinking water: A contingent valuation study in Jacksonville, FL. J. Environ. Manage., 203: 413–421 **(9 pages)**.

Dinas LH DKI Jakarta, (2021). Laporan Akhir Pemantauan Kualitas Air Tanah Tahun 2021. **(1326 pages).**

Diskominfotik Pemprov. DKI Jakarta, (2023). Tentang Jakarta.

Fadly, M.; Prayogi, T.E.; Mohamad, F.; Zulfaris, D.Y.; Memed, M.W.; Daryanto, A.; Abdillah, F.; Nasution, E.M.; Sudianto, J.R.; Giarto, B.; Maliki, F., (2017). Groundwater quality assessment in Jakarta Capital region for the safe drinking water. IOP Conference Series: Mater. Sci. Eng., 180(2017): 012063 **(18 pages)**.

Geng, J.; Yang, N.; Zhang, W.; Yang, L., (2023). Public willingness to pay for green lifestyle in China: A contingent valuation method based on integrssated model. Int. J. Environ. Res. Public Health, 20(3): 2185 **(23 pages).**

Gujarati, D.N.; Porter, D.C., (2009). Basic Econometrics 5th Edition. McGraw.Hill, New York, USA**. (946 pages).**

Hatamkhani, A.; Moridi, A., (2021). Optimal development of agricultural sectors in the basin based on economic efficiency and social equality. Water Resour. Manag., 35(3): 917–932. **(16 pages).**

Haumann, T.; Quaiser, B.; Wieseke, J.; Rese, M., (2014). Footprints in the sands of time: A comparative analysis of the effectiveness of customer satisfaction and customer company identification over time. J. Mark., 78(16): 78–102. **(25 pages).**

Hermawan, S.; Hananto, S.A., (2022). Issues on water privatization under new regulation: evidence in Indonesia. Comp. Law Rev., 28: 341–366 **(26 pages)**.

Hynes, S.; Armstrong, C.W.; Xuan, B.B.; Ankamah-Yeboah, I.; Simpson, K.; Tinch, R.; Ressurreição, A., (2021). Have environmental preferences and willingness to pay remained stable before and during the global covid-19 shock?. Ecol. Econ., 189: 107142 **(13 pages)**.

Ismowati, M., (2018). Profile of pam jaya and private partners in clean water supply Jakarta (case study year 1998-2012). KnE Soc. Sci., 2018: 481–493 **(13 pages).**

Istamto, T.; Houthuijs, D.; Lebret, E., (2014). Multi-country willingness to pay study on road-traffic environmental health effects: are people willing and able to provide a number? Environ. Health. 13(1): 35 **(13 pages)**.

Jianjun, J.; Wenyu, W.; Ying, F.; Xiaomin, W., (2016). Measuring the willingness to pay for drinking water quality improvements: results of a contingent valuation survey in Songzi, China. J. Water Health. 14(3): 504–512 **(9 pages)**.

Johnson, A.G.; Amin, A.B.; Ali, A.R.; Hoots, B.; Cadwell, B.L.; Arora, S.; Avoundjian, T.; Awofeso, A.O.; Barnes, J.; Bayoumi, N.S.; Busen, K.; Chang, C.; Cima, M.; Crockett, M.; Cronquist, A.; Davidson, S.; Davis, E.; Delgadillo, J.; Dorabawila, V.; Drenzek, C.; Eisenstein, L.; Fast, H.E.; Gent, A.; Hand, J.; Hoefer, D.; Holtzman, C.; Jara, A.; Jones, A.; Kamal-Ahmed, I.; Kangas, S.; Kanishka, F.; Kaur, R.; Khan, S.; King, J.; Kirkendall, S.; Klioueva, A.; Kocharian, A.; Kwon, F.Y.; Logan, J.; Lyons, B.C.; Lyons, S.; May, A.; McCormick, D.; Mendoza, E.; Milroy, L.; O'Donnell, A.; Pike, M.; Pogosjans, S.; Saupe, A.; Sell, J.; Smith, E.; Sosin, D.M.; Stanislawski, E.; Steele, M.K.; Stephenson, M.; Stout, A.; Strand, K.; Tilakaratne, B.P.; Turner, K.; Vest, H.; Warner, S.; Wiedeman, C.; Zaldivar, A.; Silk, B.J.; Scobie, H.M., (2022). COVID-19 incidence and death rates among unvaccinated and fully vaccinated adults with and without booster doses during periods of delta and omicron variant emergence – 25 U.S. Jurisdictions. Morb. Mortal. Wkly. Rep., 71: 132–138 **(7 pages)**.

Kasim, S.; Daud, A.; Birawida, A.B.; Mallongi, A.; Arundhana, A.I.; Rasul, A.; Hatta, M., (2023). Analysis of environmental health risk from exposure to polyethylene terephthalate microplastics in refilled drinking water. Global J. Environ. Sci. Manage., 9(SI): 301-318 **(18 pages)**.

Kavosi, Z.; Jafari, A.; Keshtkaran, V.; Pourahmadi, E., (2018). Estimating willingness to pay for an improved service delivery to patients referring Namazi Hospital chemical therapy ward in Iran using contingent valuation. Asian Pacific J. Cancer Prev., 19(7): 1817–1823 **(7 pages)**.

Khan, I.; Lei, H.; Ali, G.; Ali, S.; Zhao, M., (2019). Public attitudes, preferences and willingness to pay for river ecosystem services. Int. J. Environ. Res. Public Health, 16(19): 3707 **(17 pages)**.

Koschate, N.; Hoyer, W.D., (2013). Do satisfied customers really pay a study more? The relationship between customer satisfaction and to pay willingness. Am. Mark. Assoc., 69(2): 84–96 **(13 pages)**.

Lapworth, D.J.; MacDonald, A.M.; Kebede, S.; Owor, M.; Chavula, G.; Fallas, H.; Wilson, P.; Ward, J.S.T.; Lark, M.; Okullo, J.; Mwathunga, E.; Banda, S.; Gwengweya, G.; Nedaw, D.; Jumbo, S.; Banks, E.; Cook, P.; Casey, V., (2020). Drinking water quality from rural handpump-boreholes in Africa. Environ. Res. Lett., 15: 064020 **(13 pages)**.

Mbarep, D.P.P.; Herdiansyah, H., (2019). Ecological function of green open space as water infiltration: Study in Kalijodo green open space, North Jakarta. Conference Series: J. Phys., 1381(1): 012049 **(7 pages)**.

Meutia, A.A.; Bachriadi, D.; Gafur, N.A., (2023). Environment degradation, health threats, and legality at the artisanal small-scale gold mining sites in Indonesia. Int. J. Environ. Res. Public Health, 20: 6774 **(26 pages).**

Muazzinah, M.; Majid, M.S.A.; Syathi, P.B., (2020). What determines households willingness to pay for clean water?. Econ. Dev. Anal. J., 9(4): 402–413 **(12 pages)**.

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages)**.

Moore, C.C; Corona, J.; Griffiths, C.; Heberling, M.T.; Hewitt, J.A.; Keiser, D.A.; Kling, C.L.; Massey, D.M.; Papenfus, M.; Phaneuf, D.J.; Smith, D.J.; Vossler, C.A.; Wheeler, W., (2023). Measuring the social benefits of water quality improvements to support regulatory objectives: Progress and future directions. Proc. Natl. Acad. Sci. U.S.A, 120(18): e2120247120 **(8 pages)**.

National Bureau of Statistics of China, (2022). Water Supply and Water Use in 2021.

Nurwahdah, F.R.; Alfarizi, M.; Gusti, U.A., (2023). Analysis of community based industrial waste treatment to control river water pollution. ASEAN Nat. Disasters Mitig. Educ. J., 1(1): 1–11 **(11 pages)**.

Olalekan, R.M.; O, O.A.; Ayibatonbira, A.A.; Anu, B.; Emmanuel, O.O.; Sanchez, N.D., (2019). "Digging deeper" evidence on water crisis and its solution in Nigeria for Bayelsa State: a study of current scenario. Int. J. Hydrol., 3(4): 244–257 **(14 pages)**.

Pemerintah Indonesia, (2010). Peraturan Menteri Kesehatan Republik Indonesia Nomor 492/MENKES/PER/IV/2010 tentang Persyaratan Kualitas Air Minum **(9 pages).**

Pemerintah Indonesia, (2017). Peraturan Menteri Kesehatan Republik Indonesia Nomor 32 Tahun 2017 Tentang Standar Baku Mutu Kesehatan Lingkungan dan Persyaratan Kesehatan Air untuk Keperluan Higiene Sanitasi, Kolam Renang, Solus Per Aqua, dan Pemandian Umum. Sekretariat Negara Republik Indonesia, Jakarta **(31 pages).**

Peng, Z.; Pu, H.; Huang, X.; Zheng, R.; Xu, L., (2022). Study on public willingness and incentive mechanism of ecological compensation for inter-basin water transfer in China in the carbon neutral perspective. Ecol. Indic., 143: 109397 **(13 pages)**.

Prayoga, R.; Nastiti, A.; Schindler, S.; Kusumah, S.W.D.; Sutadian, A.D.; Sundana, E.J.; Simatupang, E.; Wibowo, A.; Budiwantoro, B.; Sedighi, M., (2021). Perceptions of drinking water service of the 'off-grid' community in Cimahi, Indonesia. Water, 13: 1398 **(15 pages)**.

Rafique, M.Z.; Sun, J.; Larik, A.R.; Li, Y., (2022). Assessment of willingness to pay for pollution prevention, health and happiness: a case study of Punjab, Pakistan. Front Public Health., 10: 825387 **(12 pages).**

Rananga, H.T.; Gumbo, J.R., , (2015). Willingness to pay for water services in two communities of multiple local municipality, South Africa: A case study. J. Hum. Ecol., 49(3): 231–243 **(13 pages)**.

Rodríguez-Tapia, L.; Revollo-Fernández, D.A.; Morales-Novelo, J.A., (2017). Household's perception of water quality and willingness to pay for clean water in Mexico City. Economies, 5(2): 12 **(14 pages)**.

Sá, M.J.; Stein, U.; Bueb, B.; Bouleau, G.; Rouillé-Kielo, G., (2023). Making urban water management tangible for the public by means of digital solutions. Sustainability, 15(2): 1280 **(14 pages)**.

Salehi, M.; Odimayomi, T.; Ra, K.; Ley, C.; Julien, R.; Nejadhashemi, A.P.; Hernandez-Suarez, J.S.; Mitchell, J.; Shah, A.D.; Whelton, A., (2020). An investigation of spatial and temporal drinking water quality variation in green residential plumbing. Build. Environ., 169: 106566 **(11 pages)**.

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages)**.

Samimi, M.; Shahriari-Moghadam, M., (2023). The Lantana camara L. stem biomass as an inexpensive and efficient biosorbent for the adsorptive removal of malachite green from aquatic environments: kinetics, equilibrium and thermodynamic studies. Int. J. Phytoremediation, 25(10): 1328-1336 **(9 pages)**.

Soesilo, T.E.B.; Rezki, C.T.; Sulthonuddin, I., (2019). Oil spill response preparedness model through community participation in Teluk Penyu Beach, Cilacap Regency. J. Environ. Sci. Sustain. Dev., 2(1), 1-14 **(14 pages)**.

Sulthonuddin, I.; Mulyo, D.; Hartono; Utomo, S.W., (2018). Water quality assessment of Cimanuk River in West Java using pollution index. E3S Web. Conf., 18: 04009 **(7 pages).**

Suratin, A.; Triakuntini, E.; Herdiansyah, H., (2019). Effects of the implementation of a progressive tariffs policy on water management in DKI Jakarta, Indonesia. Environ. Socioeconomic Stud., 7(4): 36–44 **(8 pages)**.

Syaukat, Y.; Maryani, A., (2020). Willingness to pay and consumption characteristics of drinking water to the households in Katulampa Village, City of Bogor. In: IOP Conference Series: Earth Environ. Sci., 477: 012027 **(11 pages)**.

Tasong, A.C.; Abao, R.P., (2019). Design and development of an IoT application with visual analytics for water consumption monitoring. Procedia Comput. Sci., 157: 205–213 **(9 pages)**.

Tyllianakis, E.; Skuras, D., (2016). The income elasticity of willingness-to-pay (wtp) revisited: a meta-analysis of studies for restoring good ecological status (ges) of water bodies under the water framework directive (wfd). J. Environ. Manage. 182: 531–541 **(11 pages)**.

Wang, J.; Ge, J.; Gao, Z., (2018). Consumers' preferences and derived willingness-to-pay for water supply safety improvement: the analysis of pricing and incentive strategies. Sustainability, 10: 1704 **(16 pages).**

Wardhana, Y.M.A., (2020). Analysis of effectivity scheme based on risk management and efficiency for the acceleration of clean water fulfillment in Indonesia. J. Environ. Sci. Sustain. Dev., 3(1): 30–46 **(18 pages)**.

Weckroth, M.; Ala-Mantila, S.; Ballas, D.; Ziogas, T.; Ikonen, J., (2022). Urbanity, neighborhood characteristics and perceived quality of life (qol): analysis of individual and contextual determinants for perceived qol in 3300 postal code areas in Finland. Soc. Indic. Res., 164(1): 139–164 **(6 pages)**.

Xiong, Y.J.; Hao, X.R.; Liao, C.; Zeng, Z.N., (2016). Relationship between water-conservation behavior and water education in Guangzhou, China. Environ. Earth Sci., 75(1): 1–9 **(9 pages)**.

Zolfagharipoor, M.A.; Ahmadi, A., (2021). Agent-based modeling of participants' behaviors in an inter-sectoral groundwater market. J. Environ. Manage., 299: 113560 **(13 pages)**.

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ORIGINAL RESEARCH ARTICLE

Removal of ceftriaxone and ciprofloxacin antibiotics from aqueous solutions using graphene oxide derived from corn cob

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ABSTRACT

BACKGROUND AND OBJECTIVES: Preliminary studies on the exploration of carbonaceous materials from agricultural waste and their use as adsorbents for antibiotic removal have shown the potential to address a new threat to human health due to antibiotic residue. Therefore, this study developed and synthesized graphene oxide from corn cob for its efficiency in removing ceftriaxone and ciprofloxacin.
METHODS: The Hummers methods were used to synthesize graphene oxide from corn cobs. Graphene oxide was characterized using Fourier transform infrared, scanning electron microscope-energy dispersive x-ray, and x-ray diffraction instruments. During the synthesis process, antibiotic adsorption tests were extensively conducted by exploring four variables, namely dosage of adsorbent, potential hydrogen, concentration, and contact time.
FINDINGS: The result showed that graphene oxide from corn cob effectively removed 47 percent of ceftriaxone and 92.62 percent of ciprofloxacin. Furthermore, to ensure optimum use of the adsorbents, antibiotics ceftriaxone and ciprofloxacin weighing 40 milligrams and 20 milligrams. This is in addition to the initial concentrations of 14 and 2 parts per million, the potential of hydrogen 4, and contact times of 50 and 40 minutes, respectively.
CONCLUSION: In conclusion, adsorbents made from corn cobs are better at the removal of ciprofloxacin from water than the antibiotic ceftriaxone. The difference in molecular structure affected the percentage of antibiotic adsorption onto graphene oxide derived from corn cob. This study underscores the potential of the derived material as a promising adsorbent for efficiently removing ciprofloxacin from aquatic environments. The use of agricultural waste as advanced materials to address antibiotic residue pollution provided additional environmental pollution.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
55	11	3

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INTRODUCTION

Antibiotics are widely recognized for bacteriostatic properties, which effectively prevent the proliferation of bacteria and reduce the risk of death caused by bacterial infections in both humans and animals (Catteau *et al.,* 2018). However, its increasing application poses challenges in the aquatic environment, as antibiotic residues, particularly from commonly used antibiotics like ceftriaxone and ciprofloxacin (Zhu *et al.,* 2015), cannot be easily degraded. This situation contributed to the development of bacterial resistance to antibiotics (Ben *et al.,* 2019). Ceftriaxone, widely adopted for its significant effectiveness, broad range of action, and minimal risk of adverse effects, is commonly used in various medical settings, including clinics, animal husbandry, and fisheries. It is used in the treatment of diverse bacterial infections, such as pneumonia, bone, abdominal, skin, and soft tissue, including urinary tract infections (Ayele *et al.,* 2018). Despite its efficacy, the environmental impact of ceftriaxone is significant, specifically when used inappropriately or when exceeding the Maximum Residue Limit (MRL). Guo *et al.* (2017) reported that ceftriaxone treatment in mice significantly affected parameters like the histological cross-section of the distal small intestine, body weight, spleen index, immune globulin, and cytokines. This treatement is also used to treat mastitis in cows with inappropriate usage capable of contaminating antibiotic residues, negatively impacting the aquatic environment. This contamination can inhibit the development and genotoxicity of living creatures in these waters. In a research conducted by Chowdhury *et al.* (2022), it was reported that incorrect usage exceeding MRLs of antibiotics, particularly ceftriaxone, can have negative impacts on aquatic ecosystems, inhibiting the development and genotoxicity of living creatures in these waters. On the contrary, ciprofloxacin, a globally recognized fluoroquinolone, is extensively used in aquaculture, poultry farming, and clinical settings owing to its minimal toxicity, broad antibacterial spectrum, and limited development of bacterial resistance (Zhu *et al.,* 2019). The introduction of ciprofloxacin into water resources, even at low concentrations, has been associated with significant consequences such as impacting photosynthesis, altering the morphological structure of algae, and disrupting the balance of aquatic ecosystems. Furthermore, due to its widespread use and incomplete metabolism in humans and animals, ciprofloxacin residues were detected in diverse wastewater. The wastewater was generated from the pharmaceutical industry in Patancheru, India, with concentrations ranging from 28.000 to 31.000 grams per liter (g/L), hospitals in Switzerland recorded concentrations of >10 g/L. At the same time, residential towns around WWTPs in the same country reported levels between 0.255 and 0.568 g/L. Additionally, agricultural land in central China recorded concentrations ranging from 0.020 to 0.100 g/L (Honarmand *et al.,* 2022). This widespread occurrence proved ceftriaxone and ciprofloxacin are significant water pollutants that demand urgent research attention (Wakejo *et al.,* 2022). The effective removal techniques are important due to the importance of addressing antibiotic residues in the aquatic environment. Several methods, including membrane removal (Nasrollahi *et al.,* 2022), degradation (Ahmad *et al.,* 2021), electrochemical techniques (Orimolade *et al.,* 2023), and adsorption (Amari *et al.,* 2021), have been developed for antibiotic removal. The adsorption method was considered an alternative technique characterized by low cost, easy design, and operational convenience (Ehzari, *et al.,* 2022; Samimi and Nouri, 2023). This method focuses on developing efficient adsorbent materials, with numerous research reporting the successful use of various substances, including natural clays as adsorbents for the removal of humic acid from aqueous solutions (Gueu *et al.,* 2018), agricultural waste for the elimination of paracetamol (Osobamiro *et al.,* 2022), and amorphous zirconium for the removal of phosphate from water (Nuryadin and Imai, 2021). Carbon nanostructured materials are considered adsorbents due to its large surface area and excellent adsorption capacity, such as carbon nanotubes (CNTs), nanoparticles (NPs), graphene, and graphene oxide (GO) (González *et al.,* 2016). GO has become a significant focus in water treatment due to its unique properties, particularly its dispersibility in water facilitated by functional groups. However, this substance, which is conventionally synthesized from highly pure graphite is expensive and difficult to obtain from non-renewable sources (Bheel *et al.,* 2023). Tohamy *et al.* (2020) stated that the applicability of GO obtained from agricultural wastes is considered as low-cost adsorbent for Ni(II) in aqueous solution. This promoted various efforts to explore other agricultural waste materials, such as cassava peel, rice grain, soybean pulp, cotton seeds, straw, peanut shells, and corn cobs, as alternative low-cost adsorbents (Akhavan *et al.,* 2014; Samimi and Mansouri, 2023). According to Wang *et al.* (2023), corn cobs are mainly composed of the following elements carbon, hydrogen, and oxygen. The carbon content, constituting 48.12 percent (%) of the mass of corn cobs, indicates its potential as a viable raw material for the production of natural graphite and GO (Liu *et al.,* 2014). Over the last seven years, corn production in Lampung Province, based on data from the Central Bureau of Statistics (BPS), has shown a consistent upward trend. In 2021, the harvested area expanded to 10.8 hectares, producing a substantial corn production of 2.518 million tons. The increase in corn production, led to a significant rise in waste products, due to inappropriate usage. Therefore, the use of renewable, and cheap corn cob is perceived as a promising precursor for GO in producing adsorbent materials for antibiotic removal. The high carbon content in corn cobs depicts its potential as an effective and sustainable solution for this application. However, research on the specific capabilities of GO derived from corn cobs as an adsorbent material for removing antibiotics, particularly ceftriaxone and ciprofloxacin, remains limited. The main objective of this research is to assess the adsorption efficiency of GO derived from corn cobs in eliminating ceftriaxone and ciprofloxacin from water solutions. It aimed to achieve maximum adsorption efficiency by systematically adjusting major parameters in the evaluation of ceftriaxone and ciprofloxacin adsorption. These parameters including adsorbent mass, potential of hydrogen (pH), initial adsorbate concentration, and contact time, were carefully manipulated. By determining the influential factors, the present research provides practical guidance for optimizing the adsorption process in wastewater treatment and other environmental media. Optimization is important for environmental protection and preventing the negative impacts of antibiotics in the ecosystem. The optimal conditions can also reduce operational costs and the environmental impact of the process. The resulting GO was characterized using techniques such as x-ray diffraction (XRD), Fourier transform infrared (FTIR), Raman, and ultraviolet-visible (UV-Vis) spectroscopy, as well as scanning electron microscope-energy dispersive x-ray (SEM-EDX) to confirm its nature. Therefore, this research aimed to determine the optimal conditions for using corn cob-based adsorbent to remove residues of antibiotics, specifically ceftriaxone and ciprofloxacin, from wastewater. The research included synthesizing GO, material characterization, and antibiotic adsorption tests with variations in parameters such as adsorbent dosage, pH, concentration, and contact time. This research was conducted at the Analytical Chemistry and Instrumentation Laboratory, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Lampung in 2022. In addition, the characterization analyses were carried out in collaboration with the laboratory partner.

MATERIALS AND METHODS

The main material used for the preparation of GO was corn cobs obtained from local farmers in Lampung Province, Indonesia. Standard ceftriaxone and ciprofloxacin were supplied by Hexpharm Jaya, Indonesia. The chemicals used in the process included iron(III) chloride hexahydrate ($FeCl_3.6H_2O$), 37% concentrated hydrochloric acid (HCl), and 95 to 97% sulfuric acid (H_2SO_4), as well as 30% hydrogen peroxide (H_2O_2), were purchased from Supelco Sigma Aldrich. Additional reagents, such as 1.06498 of sodium hydroxide (NaOH) pellets, acetic acid (CH_3COOH) 695092 ACS reagent, methanol (CH_3OH) 179337 ACS reagent, ethanol (C_2H_6O), potassium permanganate ($KMnO_4$) 1.05082 ACS reagent, PhEur and barium chloride ($BaCl_2$) were supplied by MerckTM.

Synthesis of graphite from corn cob

The corn cob residue was sliced into small segments and thoroughly washed multiple times to remove dust and impurities. Subsequently, the segments were exposed to sunlight for two to three days and later dried in an oven at 100 degrees Celsius (°C) for 1.5 hours (h). The dried corn cobs are crushed into powder and carbonized in a furnace at 350 °C for 2 h. After cooling in a desiccator, the charcoal was finely pulverized using a mortar for the next stage. Next, 5 grams (g) of carbonized charcoal were added to 500 milliliters (mL) of distilled water and then stirred using a magnetic stirrer at 600 revolutions per minute (rpm). To this solution, 4 mL of $FeCl_3.6H_2O$ was added at a rotation speed of approximately 900 rpm at room temperature. The acidity (pH) of the mixed solution was carefully adjusted to approximately pH = 2 by gradually adding 1 molar (M) of HCl, followed by stirring at 60 °C for 5 h. The resulting solution was centrifuged to separate the supernatant from the graphite precipitate. The precipitate was washed with distilled water until neutral, and then it was gradually oven-dried.

Synthesis of GO with modified hummers

The widely used Hummers method for synthesizing GO includes $KMnO_4$ and $NaNO_3$. Presently, a more environmentally friendly approach, known as the modified Hummers method, has been developed which eliminated the use of $NaNO_3$, increased $KMnO_4$ usage, in a mixture of H_2SO_4 and H_3PO_4, to reduce the production of toxic gases (Santamaría-Juárez *et al.,* 2019). The detailed procedures for the modified Hummers method are outlined as follows: Initially, 1 g of graphite sourced from corn cobs is placed into a beaker within a fume hood. Furthermore, 23 mL of concentrated H_2SO_4 enhances graphite reactivity and speeds up the oxidation process with $KMnO_4$. Stir the mixture using a magnetic stirrer and place it in an ice bath at 0 °C for 30 minutes. Gradually introduce 3 g of $KMnO_4$ while maintaining the temperature below 10 °C to prevent temperature fluctuations and potential explosions. Raise the mixed solution to 35 °C and stir for an additional 30 minutes, then gradually add 46 mL of distilled water and increase its temperature to 98 °C, maintaining it for 15 minutes. The oxidation process was halted by adding 140 mL of distilled water to 10 mL of a 30% H_2O_2 solution and stirred for 10 minutes. Wash the resulting suspension repeatedly with a 5% HCl solution to remove the sulfate content, then test with $BaCl_2$. Repeatedly wash with distilled water until reaching pH = 5, and separate the solution from the precipitation using centrifugation at 5000 rpm for 10 minutes. Disperse the produced precipitate in 450 mL of distilled water and sonicate for 2 hours, facilitating the exfoliation of graphite oxide sheets into a single-layer GO form. Filter the solution, and dry the precipitate obtained in an oven at 60 °C for 5 h to form GO (Chen *et al.,* 2013).

Characterization of GO

The functional groups in GO were identified through Fourier-transform infrared spectroscopy (FTIR), using an Agilent Technologies FTIR 630 Cary type machine. This analysis aimed to identify the bond configuration in the synthesized GO. Simultaneously, an examination of the phases present in both graphite and GO samples was conducted using X-ray diffraction (XRD). The XRD analysis was conducted using a 2013 PANalytical X'Pert Powder PW3040/60 X-ray diffractometer in the Netherlands, equipped with a nickel (Ni) filter and generated monochromated copper-potassium (Cu-K) radiation (Ångström [Å] = 1.54060) at 40 kilovolts (kV) and 30 milliamperes (mA). The scanning process occurred in step mode, covering 2 theta angles from 0° to 80° at a rate of 2° per minute. To further investigate the GO, the surface morphology and quantitative composition were analyzed using scanning electron microscopy with SEM-EDX (EVO® MA 10).

Optimization of antibiotic adsorption

Approxiamely 40 milligram (mg) of GO was put into a glass beaker, and 20 mL of a 14 parts per million (ppm) ceftriaxone standard solution was added. The pH of the solution was adjusted from 2 to 5 using either 0.1 M HCl or 0.1 M NaOH (Samimi and Shahriari-Moghadam, 2021). After stirring for 30 minutes, the stirrer was turned off to ensure the effective dispersion of GO in the antibiotic solution. Stirring speed plays a crucial role in the adsorption process, influencing the distribution and interaction between the adsorbent (GO) and the adsorbate (antibiotic). An insufficient stirring speed may result in uneven distribution of the adsorbent mass, potentially reducing the efficiency of the adsorption process. Subsequently, GO was separated from the solution through centrifugation at 10,000 rpm for 15 minutes, aiming for a swift separation of the filtrate from GO. The filtered solution was then analyzed using a UV-Vis spectrophotometer at a wavelength of 268 nanometers (nm). For the optimization process, variations in adsorbent mass, adsorbate concentration, and contact time, were implemented. The same method and procedure were applied for the optimization of ciprofloxacin antibiotics. The experiment was conducted with three replications, and the relative standard deviation (RSD) for pH (0.63% to 3.10%), concentration (1.88% to 1.48%), adsorbent mass (1.68% to 2.83%), and contact time (0.88% to 2.50%), showed good precision for adsorption testing, with %RSD values < 5% for a 95% confidence level.

RESULTS AND DISCUSSION

Preparation and Charazterization of GO

Fig. 1 shows the processing sequence of corn cobs selected as raw materials for the production of GO. The process started with the drying of corn cobs, followed by crushing, leading to the generation of GO using the physically modified Hummers method (Chen *et al.,* 2013), and this led to the production of a powdered black susbstance. The synthesis of GO using the modified Hummers method takes ± 12 h before it can be used for the adsorption of antibiotics like ceftriaxone and ciprofloxacin. The preparation for the adsorption process lasts for an additional 3 h.

The GO obtained was further characterized using FTIR, SEM, and XRD instruments, as shown in Fig. 2. The generated FTIR spectrum in Fig. 2(b) showed distinctive features, including a hydroxyl group at a wavelength number of 3183 per centimeter (1/cm). Furthermore, absorption at wave numbers of 1897/cm, signified the presence of C-H bending groups (aromatic compounds), while the appearance of the C=C (cyclic alkene) group found in the 1580/cm spectrum indicated the existence of C-O bonds. The GO spectrum showed two absorption peaks, one at 1700/cm, indicating it contains carboxylic (-COOH) groups, and another at 1029/cm, depicting the presence of epoxy (C-O-C) functional groups. This consistency of functional groups in the FTIR spectrum with those in pure GO led to effective preparation (Chen *et al.,* 2015). The XRD results in Fig. 2(c) showed that the GO spectrum formed peaks at 10.62° and 23.42°, consistent with the research conducted by Özgan and Eskalen (2020), who reported two prominent ones at 10° and 23°. The SEM image of GO in Fig. 2(a) showed a thin sheet shape, without pores

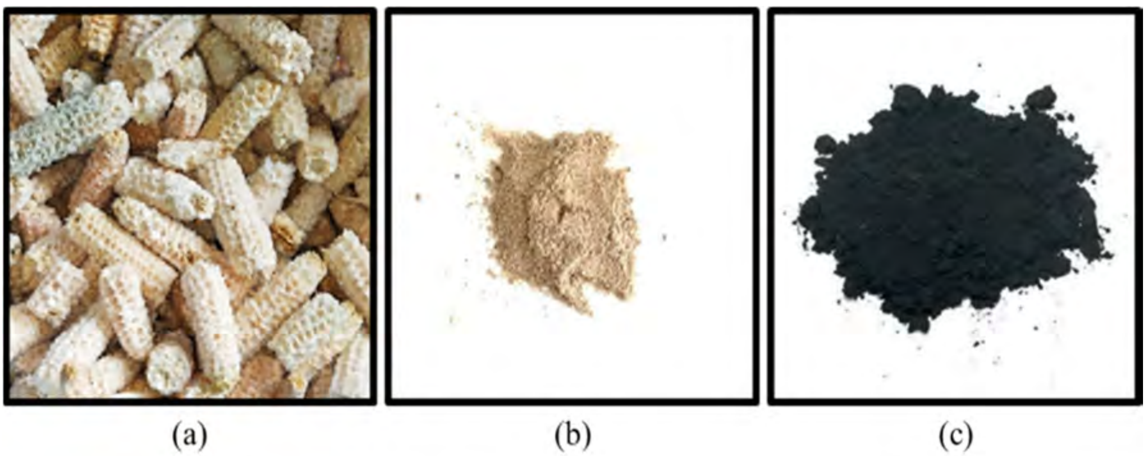


Fig. 1: Preparation of GO: (a) corn cob, (b) crushed and (c) GO derived corn cob

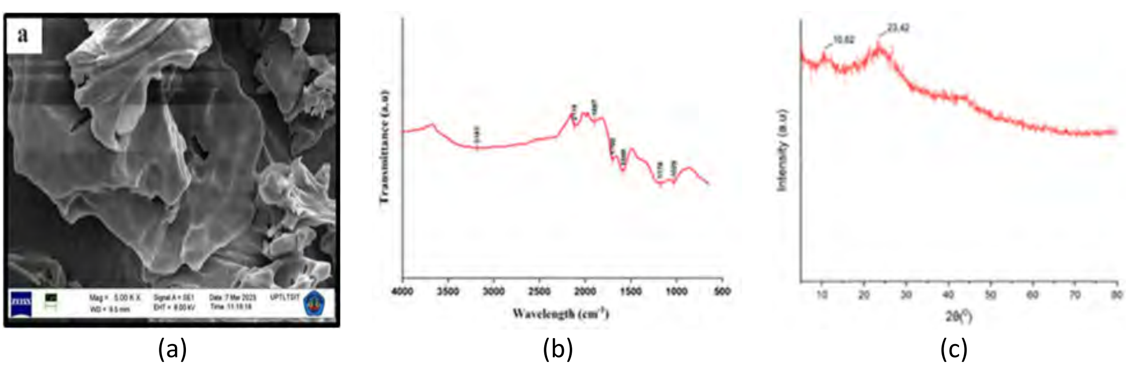


Fig. 2: (a) SEM image of GO, (b) FTIR spectrum, and (c) XRD spectrum

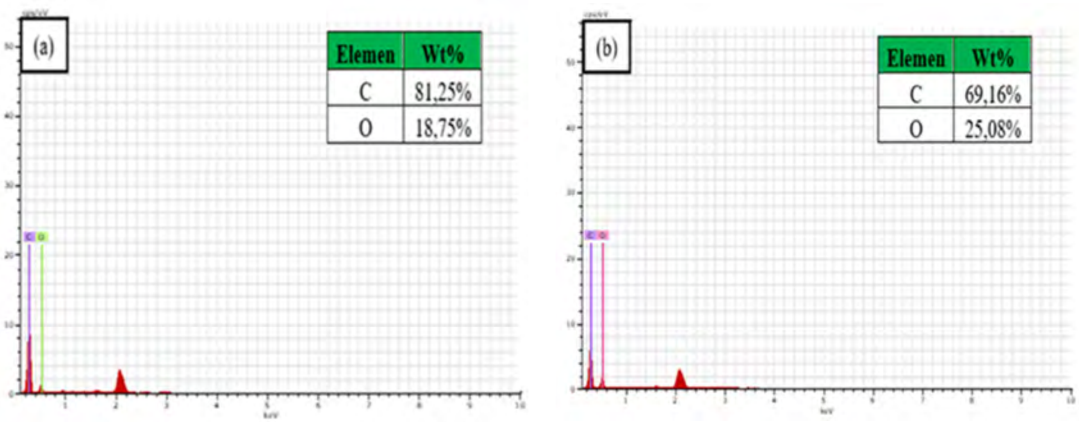


Fig. 3: EDX spectrum results on adsorbents: (a) graphite and (b) GO.

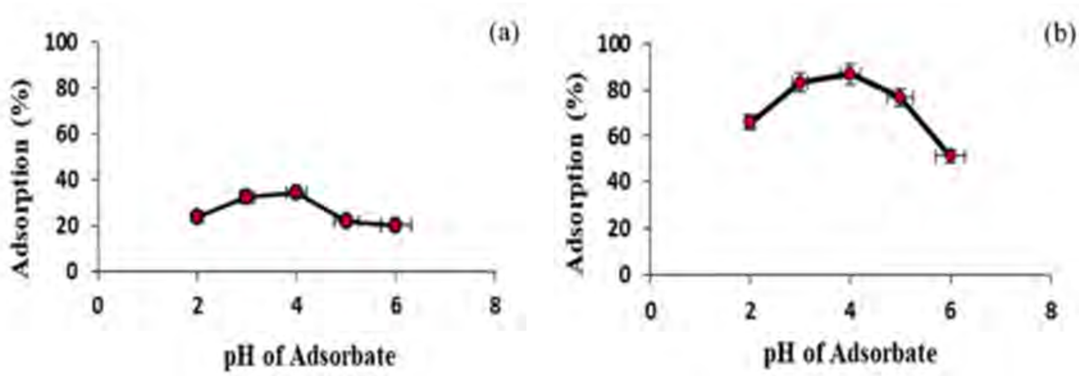


Fig. 4: Adsorption test results based on the effect of the adsorbate's optimum pH (a) ceftriaxone, and (b) ciprofloxacin

or wrinkled areas. In practice, GO has a relatively large surface that resembles a thin curtain. This confirmed the successful exfoliation procedure applied during the oxidation process and sonication, in line with the research preliminary (Naeini *et al.,* 2020).

The SEM characterization can be enhanced by using EDX to determine the elemental composition of the adsorbent. The results of GO adsorbent, illustrating the main elements as carbon (C) and oxygen (O), are shown in Fig. 3. Based on Fig. 3(a), the atomic composition of carbon (C) in graphite is 81.25%, indicating a higher number of elements. Conversely, in Fig. 3(b), the atomic percent (C) for GO is 69.16%, accompanied by oxygen percent (O) value of 18.75% and 25.08%, in graphite and GO, respectively. An increase in the oxygen percent indicates the successfully oxidation of GO, and this is in accordance with the adopted method, which mandates an increase in the content of this element in graphite oxide for the formation of GO (Kigozi *et al.,* 2020). Therefore, the combined SEM surface and EDX spectrum confirm the successful production of GO, presenting a smooth surface and sheet-like structure with high percentages of carbon (C) and oxygen (O) elements.

Adsorption optimization

Effect of pH adsorbate

Figs. 4(a) and 4(b) shows the results of the adsorption tests investigating the optimal pH effect for ceftriaxone and ciprofloxacin adsorption. The results showed that the adsorption efficiency of both ceftriaxone and ciprofloxacin compounds by GO reached its maximum level at pH = 4.

Ceftriaxone and ciprofloxacin underwent cationic and anionic transitions depending on the acidity,

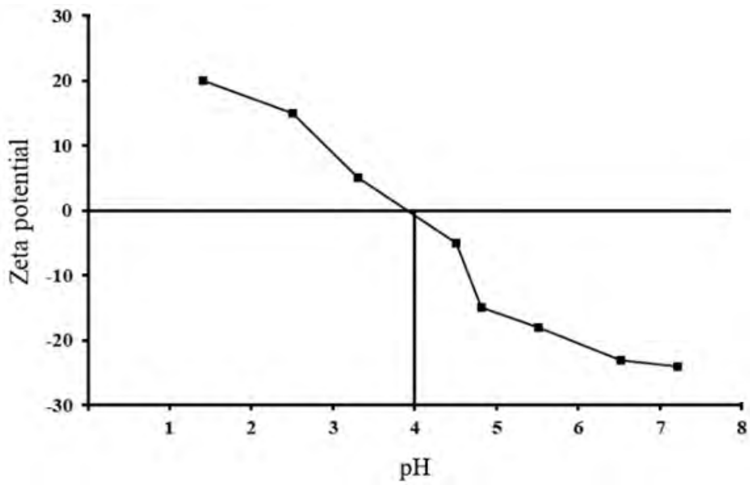


Fig. 5: Point of zero charge potential of GO

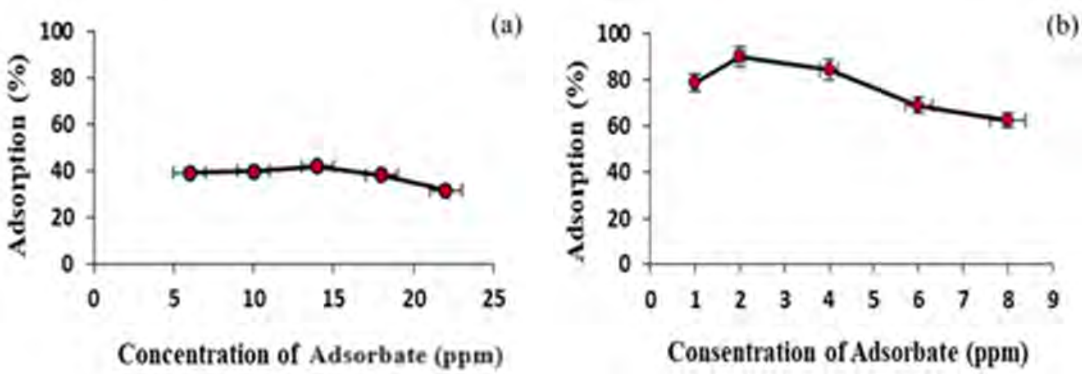


Fig. 6: Adsorption test to asses the influence of the optimal concentration of (a) ceftriaxone and (b) ciprofloxacin

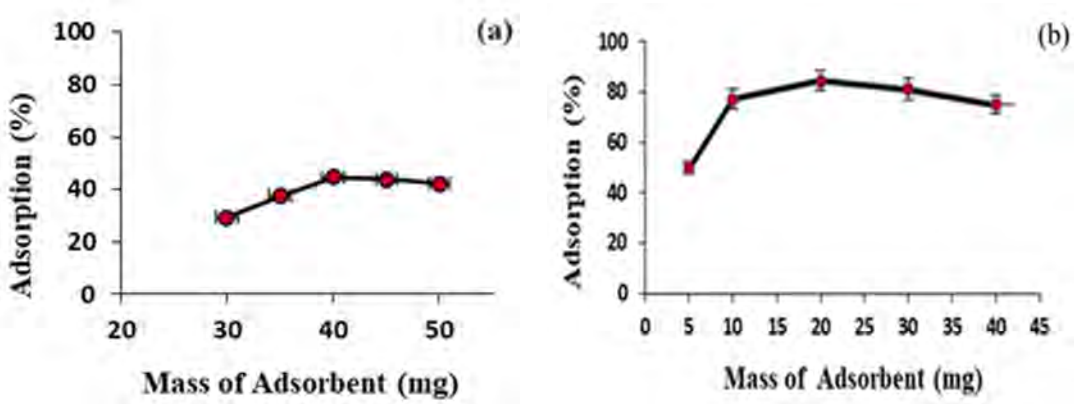
with protonation of the dimethyl-ammonium group resulting in a positive charge, while the loss of a proton from the carbonyl system led to a negative charge. GO point of zero charge (PZC), typically falls between 3.5 and 4, as shown in Fig. 5 (Li *et al.,* 2023).

The point of zero charge potential of GO is positively and negatively charged below and above the PZC (Li *et al*., 2023). This difference in charge led to a strong electrostatic attraction between the oppositely charged ceftriaxone and ciprofloxacin and the functional groups of GO. The process led to a high adsorption capacity, in line with previous research (Yu *et al*., 2016). As the pH increases to 7.0, GO decresaes, thereby enhancing its electronegativity and at 7, both GO and antibiotics carry negative charges, thereby intensifying the electrostatic repulsion (Chen *et al*., 2015).

Effect of initial adsorbate concentration

Fig. 6 shows the results of the adsorption test, examining the impact of the optimal concentration of the adsorbates, specifically (a) ceftriaxone and (b) ciprofloxacin.

In Fig. 6(a), the optimal adsorbate concentration of 14 ppm, achieved a 41.95% adsorption rate. However, at concentrations of 18 and 22 ppm, the adsorption percentage decreased, indicating potential saturation of the adsorbent, and reduced absorption efficacy. Higher adsorbate concentrations tend to saturate more adsorbent pores, leading to a subsequent reduction in adsorption capacity. The prolonged contact between the GO adsorbent and ceftriaxone solution, which leads to increased adsorbate adsorption until equilibrium is reached, is in line with previous research (Tohamy *et al*., 2020). In the



(a) (b)

Fig. 7: The outcomes of the adsorption test, focusing on the influence of the optimal adsorbent mass, are presented in (a) for ceftriaxone and (b) for ciprofloxacin.

adsorption process of ciprofloxacin by GO, optimal performance was observed at a concentration of 2 ppm, achieving a significant adsorption rate of 90.05%, as shown in Fig. 6(b). Meanwhile, at higher concentrations of 4 and 6 ppm, the adsorption rates gradually reduced. Lower adsorbate concentrations covering fewer active sites, decreasing the likelihood of adsorbate saturation in GO pores. The long contact time between the adsorbent and adsorbate increased the adsorbate amount on the surface of the adsorbent, which led to saturation and decrease in adsorption capacity (Yadav *et al*., 2018).

Effect of adsorbent mass

Fig. 7 shows the results of the adsorption test, examining the impact of varying adsorbent mass on both (a) ceftriaxone and (b) ciprofloxacin. The findings showed a connection between the adsorption rate and the mass of GO in ceftriaxone compounds. The optimal adsorbent mass condition was detected at 40 mg, achieving a 44.65% adsorption rate. However, within the range of 30 mg to 40 mg adsorbent mass, there was an increase in the levels of adsorbate absorbed. At 40 mg, the adsorbent mass reached its peak adsorption efficiency, attaining a point where the adsorbate absorbed is equal to the amount left in the solution, thereby maximizing the adsorption capacity. This enhancement in adsorption was attributed to the rise in active sites on the surface of the adsorbent, facilitating increased adsorbate absorption. Conversely, at a mass of 45 mg, there was a decrease in adsorption efficiency due to denser adsorbent particles, resulting in overlapping events during the process as shown in Fig. 7a. The increased density diminishes the active sites on the adsorbent, reducing its capacity to absorb adsorbate. This phenomenon is also similar to the findings reported in preliminary research (Beifing Lv *et al*., 2021).

Fig. 7(b) shows the relationship between the adsorption rate and the mass of GO in ciprofloxacin compounds. It is evident that the most effective adsorption process of ciprofloxacin compounds by GO occurred at 20 mg adsorbent mass at a rate of 84.55%. However, the use of adsorbent masses of 30 and 40 mg resulted in a decrease in the adsorption rate. This decline was attributed to a larger adsorbent mass causing increased density, leading to overlapping events between the particles. Consequently, these active sites were not maximized during the adsorbate absorption process (Bhaumik *et al.,* 2012), which is in accordance with preliminary research by (Arias *et al.,* 2020).

Effect of contact time

The results of the adsorption test, in respect to examining the impact of the optimal adsorbent mass for ceftriaxone (a) and ciprofloxacin (b) over different time intervals are shown in Fig. 8. The ceftriaxone adsorption test revealed a positive correlation between contact time and the adsorption of antibiotics, with a gradual increase as time progressed. This was attributed to the prolonged

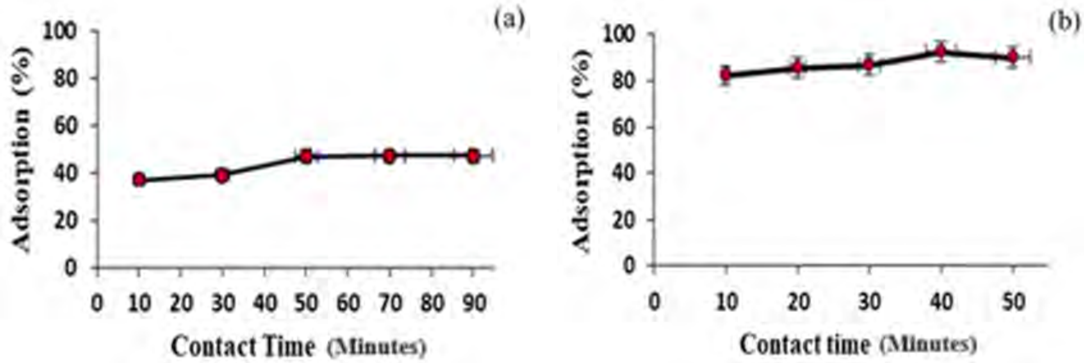


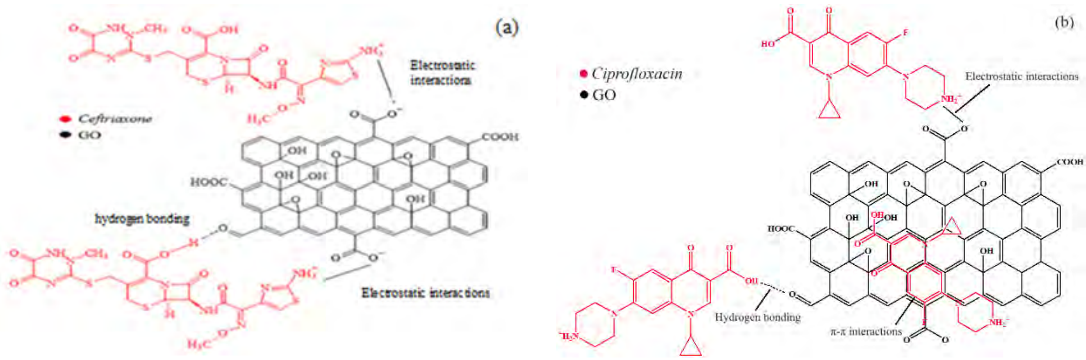
Fig. 8: The outcomes of the adsorption test, focusing on the influence of the optimal time for adsorbent mass, are presented in (a) for ceftriaxone and (b) for ciprofloxacin

Table 1: Adsorption capacities of different biosorbents

Biosorbent	Analyte	Adsorption level (%)	Contact time	Sources
Palm kernel Shell	Paracetamol	76.6	80 min	Osobamiro *et al.*, 2022
Calcium / iron (Ca/Fe)-layered double hydroxides (LDHs) from eggshell	Tetracycline	40-45	90 min	Abed *et al.*, 2023
Activated carbon from vine wood	Cephalexin	80	8 h	Pouretedal *et al.*, 2014
GO/Fe_3O_4-$SrTiO_3$	Cefotaxime	80	180 min	Nodeh and Saresti, 2016
Magnetic rod-like hydroxyapatite and MIL-101(Fe) metal–organic framework nanocomposite	Ciprofloxacin	26	25 min	Beiranvand *et al.*, 2022
Kaolin-Fe_3O_4	Cefixime	60	60 min	Azzouzi *et al.*, 2022
Corn cob	Ceftriaxone	47.04	50 min	The current study
Corn cob	Ciprofloxacin	92.62	40 min	The current study

contact time between the adsorbent and the adsorbate, enhancing its ability to be properly binded. At contact times ranging from 50 to 70 minutes, the percent adsorption value stabilized at 47%, with the most efficient contact time identified at 50 minutes as shown in Fig. 8a. Examining the outcomes at varying contact times in Fig. 8(b), the adsorption of ciprofloxacin by GO reached optimal conditions at 40 minutes, achieving a 92.62% adsorption rate. However, a reduction in adsorption rate was observed at a contact time of 50 minutes. This was attributed to the interaction between GO and ciprofloxacin compounds, leading to less-than-optimal GO adsorption power due to saturation in the adsorbent. The crowded surface area of the adsorbate causes ciprofloxacin compounds to desorb again (Yusof and Malek, 2009). This pattern is in line with the the findings reported in previous research (Asman *et al.*, 2016).

The adsorption level results in this research were compared with findings from several published investigations, as shown in Table 1. The GO adsorbent material sourced from corn cobs showed a significantly high adsorption capacity for the antibiotic ciprofloxacin. However, its adsorption capacity for ceftriaxone was found to be moderate compared to other biosorbents. The highest removal efficiency, reaching approximately 92.62%, was achieved using GO derived from corn cobs. According to Tohamy *et al.* (2020), GO derived from sugar cane bagasse showed the highest removal efficiency for Ni (III), reaching approximately 85.06%. Both sets of results were consistent with the Langmuir isotherm model, although it showed a significant difference in the removal efficiency of ceftriaxone. The maximum removal achieved with GO was 47%, which is lower than the highest one attained with an activated carbon-based TiO_2 composite, reaching 96.6% (Abdullah *et al.*, 2023). In addition, the isotherm model followed that of Freundlich in both cases.



(a) (b)

Fig. 9: Adsorption mechanism (a) ceftriaxone and (b) ciprofloxacin.

Table 2: Kinetics parameters for the adsorption of ceftriaxone and ciprofloxacin on GO.

Adsorbent	Adsorbate	Kinetic models			
		Pseudo-first-order		Pseudo-second-order	
		K_1	R^2	K_2	R^2
GO	Ceftriaxone	0.040	0.808	3.544	0.998
GO	Ciprofloxacin	0.015	0.734	0.150	0.848

Adsorption mechanism

Based on the results of the adsorption process, it was observed that the antibiotic ceftriaxone had a lower percentage compared to ciprofloxacin. This variation in adsorption behavior is due to the specific interaction mechanisms between ceftriaxone and ciprofloxacin on the GO surface, as shown in Fig. 9. The adsorption mechanisms that occur between GO and both antibiotics are hydrogen bonding, electrostatic and π-π interactions. Meanwhile, the benzene and nitrogen-heteroaromatic rings attached to the fluorine as well as ciprofloxacin and ceftriaxone groups, respectively can engage in π interactions.

The benzene ring contained in GO functions as a π electron donor, while the aromatic one in ciprofloxacin acts as an acceptor in electron interactions. The presence of two C=O groups and one OH, facilitates the formation of hydrogen bonds with oxygen-containing groups found on GO (Gamoń *et al.,* 2022). However, due to its aromatic benzene ring, ciprofloxacin showed a higher propensity for engaging in π-π interactions. In contrast, the structural characteristics of ceftriaxone makes it less likely to participate in π-π interactions, due to the lack of aromatic benzene rings. The patterned structure of the ceftriaxone molecule also hindered its ability to form strong and specific bonds with the GO surface, resulting in weaker interactions and observed lower adsorption percentage. Molecules with ordered structures, such as ciprofloxacin, tend to form stronger bonds with the solid or liquid surfaces due to its organized interaction sites (Zhang *et al.,* 2017). The smaller molecular shape, enhances its efficiency in reaching active adsorption sites. This is in line with the research conducted by Arias *et al.* (2020), which stated molecule size and shape significantly impact absorption efficiency, with smaller ones easily reaching adsorption sites. The influence of molecular structure on adsorption capacity arises from the ability of molecules with more active sites to form additional adsorption bonds, resulting in a greater percentage (Kuroki *et al.,* 2019).

Adsorption kinetics and adsorption isotherm

The simulation of adsorption kinetics was conducted using the pseudo-first and second-order models, as shown in Table 2 and Fig. 10.

The higher R^2 values, was used to evaluate the fit of the data and ensure it is line with either the pseudo-first or second-order models (Samimi and Shahriari-Moghadam, 2023). Examining the results of the adsorption kinetics for ceftriaxone and ciprofloxacin

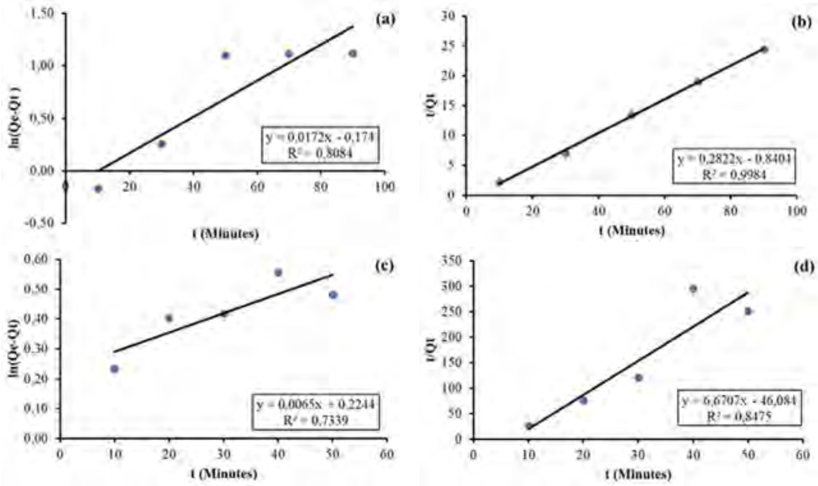


Fig. 10: Kinetic model graph of (a) pseudo-first-order ceftriaxone; (b) pseudo-second-order ceftriaxone; (c) pseudo-first-order ciprofloxacin and (d) pseudo-second-order ciprofloxacin

compounds, it was observed that the pseudo-first-order model poorly characterized antibiotic adsorption, due to its significantly small regression value. Conversely, the pseudo-second-order model established a more accurate and linear relationship, as reflected in its higher regression values. This supports the notion of a pseudo-second-order kinetic model for the adsorption process. In line with other research, Tang *et al.* (2013), reported excellent outcomes for the pseudo-second-order model in the adsorption of antibiotics such as ciprofloxacin and norfloxacin on reduced graphene oxide-M (RGO-M) surfaces. The formulas for pseudo-first and second-order reactions are expressed in Eqs. 1 and 2 (Samimi, 2024).

$$\log\left(q_e - q_t\right) = log\left(q_e\right) - \frac{K_1 t}{2,303} \qquad (1)$$

$$\frac{t}{q_t} = \frac{1}{h} - \frac{t}{q_e} \qquad (2)$$

$$t\frac{1}{2} = \frac{1}{K_2 q_e^{\,2}}$$

Where;

q_e and q_t are the amounts of Ceftriaxone and Ciprofloxacin adsorbate at equilibrium and time (t), respectively, measured in milligrams per gram (mg/g); K_1: is the pseudo-first-order rate constant per minute (/min); t1/2: the time required for the adsorption to take up half as many compounds as its equilibrium values per minute (min); h: K_2qe^2 is the initial adsorption rate as milligrams per minute (mg/min); K_2 is the pseudo-second-order rate constant in /min.

The Langmuir equation model using Eq. 3 (Samimi *et al.,* 2023).

$$\frac{C_e}{q_e} = \frac{1}{K_L Q_{max}} + \frac{1}{Q_{max}} C_e \qquad (3)$$

Where;

C_e: is the equilibrium concentration of adsorbate (mg/L).

q_e: unit mass of adsorbent (mg/g).

K_L: Langmuir constant related to the measure of affinity of the adsorbate for adsorbent (L/mg).

Q_{max}: amount of adsorbate per unit mass of adsorbent (mg/g).

The Freundlich model is represented using Eq. 4 (Azimi *et al.,* 2019; Mohadesi *et al.,* 2023).

$$\log q_e = log\,\mathrm{K}_F + \frac{1}{\mathrm{n}} \log C_e \qquad (4)$$

Where;

q_e: unit mass of adsorbent (mg/g).

C_e: is the equilibrium concentration of adsorbate

Table 3: Parameters of the ceftriaxone and ciprofloxacin adsorption isotherm on GO

Antibiotics	Adsorption Isotherm	Parameter 1	Parameter 2	R^2
Ceftriaxone	Langmuir	K_L = 1.274 L/mg	Qe = 3.021 mg/g	0.6177
	Freundlich	K_F = 2.116 (mg/g).(L/mg)$^{1/n}$	n = 1.243	0.9156
Ciprofloxacin	Langmuir	K_L = 1.445 L/mg	Qe = 2.065 mg/g	0.9101
	Freundlich	K_F = 3.235 (mg/g).(L/mg)$^{1/n}$	n = 1.854	0.7415

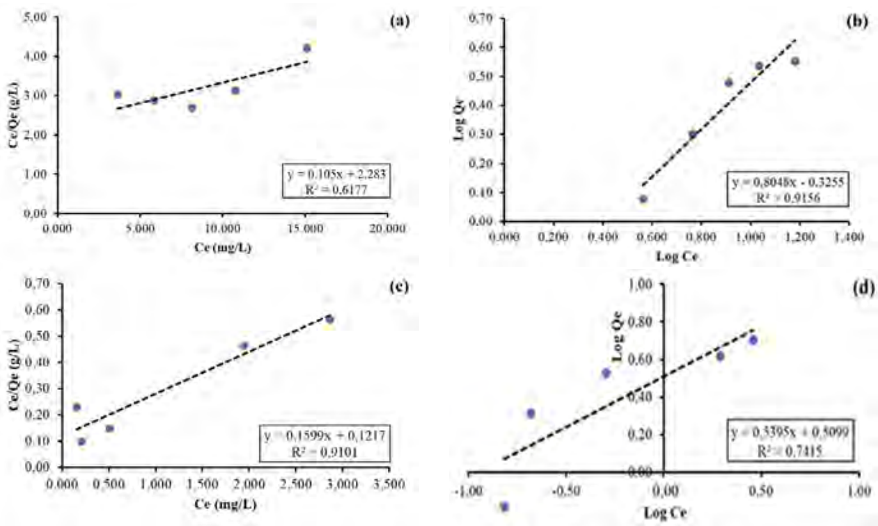


Fig. 11: Isotherm model graph (a) langmuir ceftriaxone; (b) freundlich ceftriaxone; (c) langmuir ciprofloxacin and (d) freundlich ciprofloxacin

(mg/L).

K_F: is the Freundlich constant for adsorption capacity (mg/g).

n: Freundlich index, which describes the degree of adsorption and surface heterogeneity.

A larger n value indicates stronger adsorption (Samimi and Safari, 2022), in addition the equilibrium data were subjected to further analysis using the Langmuir and Freundlich isotherm models, as shown in Table 3 and Fig. 11. The regression value (R^2) in Table 2 shows that in the adsorption process, ciprofloxacin has the highest R^2 value, following the Langmuir model (R^2) of 0.9101. However, ceftriaxone tends to adhere more closely to the Freundlich model (R^2) of 0.9156. The presence of chemical bonds showed that the adsorption of ciprofloxacin included chemical adsorption. These chemical bonds found in ciprofloxacin and GO include hydroge, and π-π bonds, as well as electrostatic interactions. The result obtained also showed that chemical adsorption interactions are less effective in the adsorption of ceftriaxone (Asman *et al.,* 2016).

CONCLUSION

In conclusion, the current study investigated the adherence of ceftriaxone and ciprofloxacin to graphene oxide (GO) derived from corn cobs, revealing intriguing and conspicuous findings. GO from corn cobs were subjected to FTIR analysis, identifying functional groups, mainly hydroxyl and carboxyl, enhancing the interaction potential of active sites on GO with other molecules. The SEM result showed that a smooth surface had been formed, constituting a thin monolayer sheet on the obtained GO. However, through careful experimentation, the ideal conditions for the adsorption of ceftriaxone and ciprofloxacin compounds were discovered. Overall 40 mg and 20 mg of adsorbent masses performed effectively with antibiotic concentrations of 14 ppm and 2 ppm, a pH level of 4, and contact times of 50 minutes and 40 minutes, respectively. These findings focused on the importance of precise experimental optimization in enhancing the removal efficiency of these antibiotics. The adsorption test for ciprofloxacin and ceftriaxone followed a pseudo-second-order model. Ciprofloxacin and ceftriaxone had a significant removal efficiency of 92.62%, and 47%, respectively. The adsorption isotherms were in line with the Langmuir Model (R^2 = 0.9101) for ciprofloxacin, while ceftriaxone tended to follow the Freundlich Model (R^2 = 0.9156). This study reported the potential of the derived material as a promising adsorbent for efficiently removing ciprofloxacin from aquatic environments. Although these results were promising, it was evident that more work needed to be done to enhance the effectiveness of the adsorbent in eliminating ceftriaxone, allowing for broader applications with minimal environmental impact. The present study contributed to the scientific understanding of adsorption processes and also showed the potential of using adsorbents derived from agricultural waste for sustainable water treatment. This alternative method addressed both antibiotic residue pollution and the challenges associated with agricultural waste, presenting a promising path for eco-friendly water treatment practices, and contributing to the resolution of interconnected environmental issues.

AUTHOR CONTRIBUTIONS

Rinawati designed the field experiment, organized the study and discussion, and contributed to the preparation of the manuscript. M.D. Imelda conducted FTIR and SEM data analysis and interpreted the results. D.R. Mythia performed data optimization analysis, XRD, and kinetic data analysis. A. Rahmawati prepared tables and figures and interpreted the results. A.A. Kiswandono supervised the experiment and contributed to the preparation of the manuscript. F.H. Latief implemented neural network analysis and prepared related text and figures. S. Mohamad participated in the interpretation of results and contributed to manuscript preparation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degrees Celsius
[Å]	Ångström
$BaCl_2$	Barium chloride
BPS	Badan pusat statistik (in indonesian) / central bureau of statistics
C_2H_6O	Ethanol
CH_3COOH	Acetic acid
CH_3OH	Methanol
/cm	Per centimeter
CNTs	Carbon nanotubes
Cu-K	Copper-potassium
Eqs.	Equation
$FeCl_3.6H_2O$	Iron(III) chloride hexahydrate
Fig.	Figure
FTIR	Fourier transform infrared
g	Grams
g/L	Gram per liter

GO	Graphene oxide
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
h	Hour
HCl	Hydrochloric acid
K	Constant
K_2qe^2	The initial adsorption rate as milligram per gram.minutes
$KMnO_4$	Potassium permanganate
kV	Kilovolts
L/mg	Liter per milligram
M	Molar
mA	Milliamperes
mg	Milligrams
mg/g	Milligram per gram
mg/g.min	Milligram per gram.minutes
min.	Minute
/min	Per minute
mL	Milliliters
MRL	Maximum Residue Limit
NaOH	Sodium hydroxide
Ni	Nickel
nm	Nanometer
NPs	Nanoparticles
pH	Potential of hydrogen
ppm	Parts per million
PZC	Point of zero charge
q_e	The amount of ceftriaxone and ciprofloxacin adsorbate at equilibrium
q_t	the amount of ceftriaxone and ciprofloxacin adsorbate at time
R^2	Regression
RGO	Reduced graphene oxide
rpm	Revolutions per minute
RSD	Relative standard deviation
SEM-EDX	Scanning electron microscope-energy dispersive x-ray
t	Time
UV-Vis	Ultra violet-visible
XRD	X-ray diffraction

REFERENCES

Azimi, N.; Azimi, P.; Samimi, M.; Mansouri Jalilian, T., (2019). Ultrasonic-assisted adsorption of Ni (II) ions from aqueous solution onto Fe3O4 nanoparticles. Adv. Nanochem., 1(2): 66-72 **(7 pages).**

Abdullah, M.; Mateen, F.; Iqbal, J.; Rehman, M.S.U.; Khalid, U.; Al-Hartomy, O.A.; Arshad, S.N.; Al-Sehemi, A.G.; Algarni, H.; Fazal, T., (2023). Removal of ceftriaxone sodium antibiotic from pharmaceutical wastewater using an activated carbon based TiO_2 composite: Adsorption and photocatalytic degradation evaluation. Chemosphere., 317: 1-13 **(13 pages).**

Abed, M.F.; Faisal, A.A.H., (2023). Calcium/iron-layered double hydroxides-sodium alginate for removal of tetracycline antibiotic from aqueous solution. Alex. Eng. J., 63: 127-142 **(16 pages).**

Ahmad, F.; Zhu, D.; Sun, J., (2021). Environmental fate of tetracycline antibiotics: degradation pathway mechanisms, challenges, and perspectives. Environ. Sci. Eur., 33: 1–17 **(17 pages).**

Akhavan, O.; Bijanzad, K.; Mirsepah, A., (2014). Synthesis of graphene from natural and industrial carbonaceous wastes. RSC Adv., 4: 20441–20448 **(8 pages).**

Amari, A.; Alzahrani, F.M.; Katubi, K.M.; Alsaiari, N.S.; Tahoon, M.A.; Rebah, F.B., (2021). Clay-polymer nanocomposites: preparations and utilization for pollutants removal. Materials. 14: 1–21 **(21 pages).**

Arias, F.A.; Guevara, M.; Tene, T.; Angamarca, P.; Molina, R.; Valarezo, A.; Salguero, O.; Gomez, C.V.; Arias, M.; Caputi, L.S., (2020). The adsorption of methylene blue on eco-friendly reduced graphene oxide. Nanomaterials., 10: 1-18 **(18 pages).**

Asman, S.; Mohamad, S.; Sarih, N.M., (2016). Study of the morphology and the adsorption behavior of molecularly imprinted polymers prepared by reversible addition-fragmentation chain transfer (raft) polymerization process based on two functionalized β-cyclodextrin as monomers. J. Mol. Liq., 214: 59–69 **(11 pages).**

Ayele, A.A.; Gebresillassie, B.M.; Erku, D.A.; Gebreyohannes, E.A.; Demssie, D.G.; Mersha, A.G.; Tegegn, H.G., (2018). Prospective evaluation of ceftriaxone use in medical and emergency wards of gondar university referral hospital, Ethiopia. Pharmacol. Res. Perspect., 6: 1-7 **(7 pages).**

Azzouzi, L.E.; Aggadi, S.E.; Ennouhi, M.; Ennouari, A.; Kabbaj, O.K.; Zrineh, A., (2022). Removal of the Amoxicillin antibiotic from aqueous matrices by means of an adsorption process using Kaolinite clay. Sci. Afr., 18: 1-10 **(10 pages).**

Beifeng Lv.; Yu, W.; Luo, W.; Qian, B.; Asefa, M.B.; Li, N., (2021). Study on the adsorption mechanism of graphene oxide by calcareous sand in south china sea. Adsorp. Sci. Technol., 2021: 1–15 **(15 pages).**

Beiranvand, M.; Farhadi, S.; Mohammadi-Gholami, A., (2022). Adsorptive removal of tetracycline and ciprofloxacin drugs from water by using a magnetic rod-like hydroxyapatite and MIL-101(Fe) metal–organic framework nanocomposite. RSC Adv., 12: 34438–34453 **(16 pages).**

Ben, Y.; Fu, C.; Hu, M.; Liu, L.; Wong, M.H.; Zheng, C., (2019). Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: a review. Int. J. Environ. Res., 169: 483–493 **(11 pages).**

Bhaumik, R.; Mondal, N.K.; Das, B.; Roy, P.; Pal, K.C.; Das, C.; Baneerjee, A.; Datta, J.K., (2012). Eggshell powder as an adsorbent for removal of fluoride from aqueous solution: equilibrium, kinetic and thermodynamic studies. J. Chem., 9: 1457–1480 **(24 pages).**

Bheel, N.; Mohammed, B.S.; Ali, M.O.A.; Shafiq, N.; Radu, D., (2023). Effect of graphene oxide as a nanomaterial on the bond behaviour of engineered cementitious composites by applying rsm modelling and optimization. J. Mater. Res. Technol., 26: 1484–1507 **(24 pages).**

Catteau, L.; Zhu, L.; Van Bambeke, F.; Quetin-Leclercq, J., (2018). Natural and hemi-synthetic pentacyclic triterpenes as antimicrobials and resistance modifying agents against staphylococcus aureus: a review. Phytochem. Rev., 17: 1129–1163 **(35 pages).**

Chen, H.; Gao, B.; Li, H., (2015). Removal of sulfamethoxazole and ciprofloxacin from aqueous solutions by graphene oxide. J. Hazard. Mater., 282: 201–207 **(7 pages).**

Chen, J.; Yao, B.; Li, C.; Shi, G., (2013). An improved Hummers method for eco-friendly synthesis of graphene oxide. Carbon., 64: 225-229 **(5 pages).**

Chowdhury, J.; Mukherjee, R.; Dutta, D.; Mandal, T.K.; Basu, T.; Mondal, S., (2022). Evaluation of Ceftriaxone Residue in Cow Milk and its Toxicity on Danio rerio. J. Food Sci. Nutr. Res., 5: 716-723 **(8 pages).**

Ehzari, H.; Safari, M.; Samimi, M.; Shamsipur, M.; Gholivand, M.B, (2022). A highly sensitive electrochemical biosensor for chlorpyrifos pesticide detection using the adsorbent nanomatrix contain the human serum albumin and the Pd: CdTe quantum dots. Microchem. J., 179: 107424 **(10 pages).**

Gamoń, F.; Tomaszewski, M.; Cema, G.; Ziembińska-Buczyńska, A., (2022). Adsorption of oxytetracycline and ciprofloxacin on carbon-based nanomaterials as affected by pH. Arch. Environ. Protect., 48: 34–41 **(8 pages).**

González-Sálamo, J.; Socas-Rodríguez, B.; Hernández-Borges, J.; Rodríguez-Delgado, M.A., (2016). Nanomaterials as sorbents for food sample analysis. Trends Anal. Chem., 85: 203–220 **(18 pages).**

Gueu, S.; Finqueneisel, G.; Zimny, T.; Bartier, D.; Yao, B.K., (2018). Physicochemical characterization of three natural clays used as adsorbent for the humic acid removal from aqueous solution. Adsorp. Sci. Technol., 37: 77–94 **(18 pages).**

Guo, Y.; Yang, X.; Qi, Y.; Wen, S.; Liu, Y.; Tang, S.; Huang, R.; Tang, L., (2017). Long-term use of ceftriaxone sodium induced changes in gut microbiota and immune system. Sci. Rep., 7: 1-9 (**9 pages).**

Honarmand, M.; Naeimi, A.; Rezakhani, M.S.; Chaji, M.A., (2022). Ni/NiO doped chitosan-cellulose based on the wastes of barley and shrimp for degradation of ciprofloxacin antibiotic. J. Mater. Res. Technol., 18: 4060–4074 **(15 pages).**

Kigozi, M.; Koech, R.K.; Kingsley, O.; Ojeaga, I.; Tebandeke, E.; Kasozi, G.N.; Onwualu, A.P., (2020). Synthesis and characterization of graphene oxide from locally mined graphite flakes and its supercapacitor applications. Results Mater., 7: 1-12 **(12 pages).**

Kuroki, A.; Hiroto, M.; Urushihara, Y.; Alcantara-Avila, J.R., (2019). Adsorption mechanism of metal ions on activated carbon. Adsorption. 25: 1251–1258 **(8 pages).**

Li, Z.; Jiang, H.; Wang, X.; Wang, C.; Wei, X., (2023). Effect of ph on adsorption of tetracycline antibiotics on graphene oxide. Int. J. Environ. Res. Public Health., 20: 1-16 **(16 pages).**

Liu, X.; Zhang, Y.; Li, Z.; Feng, R.; Zhang, Y., (2014). Characterization of corncob-derived biochar and pyrolysis kinetics in comparison with corn stalk and sawdust. Bioresour. Technol., 170: 76–82 **(7 pages).**

Mohadesi, M.; Gouran, A.; Darabi, F.; Samimi, M., (2023). Sunflower seed pulp ash as an efficient and eco-friendly adsorbent for Congo red uptake: characteristics, kinetics, and optimization. Water Pract. Technol., 18 **(12 pages).**

Naeini, A.H.; Kalaee, M.R.; Moradi, O.; Khajavi, R.; Abdouss, M., (2020). Synthesis, characterization and application of carboxylmethyl cellulose, guar gam, and graphene oxide as novel composite adsorbents for removal of malachite green from aqueous solution. Adv. Compos. Hybrid. Mater., 5: 335–349 **(15 pages).**

Nasrollahi, N.; Vatanpour, V.; Khataee, A., (2022). Removal of antibiotics from wastewaters by membrane technology: limitations, successes, and future improvements. Sci. Total Environ., 838: 1–21 **(21 pages).**

Nodeh, H.R.; Sereshti, H., (2016). Synthesis of magnetic graphene oxide doped with strontium titanium trioxide nanoparticles as nanocomposite for the removal of antibiotics from aqueous media. RSC Adv., 6: 1-27 **(27 pages).**

Nuryadin, A., Imai, T., (2021). Application of amorphous zirconium (hydr) oxide/MgFe layered double hydroxides composite in fixed-bed column for phosphate removal from water. Global J. Environ. Sci. Manage., 7: 485-502 **(18 pages).**

Orimolade, B.O.; Oladipo, A.O.; Idris, A.O.; Usisipho, F.; Azizi, S.; Maaza, M.; Lebelo, S.L.; Mamba, B.B., (2023). Advancements in electrochemical technologies for the removal of fluoroquinolone antibiotics in wastewater: a review. Sci. Total Environ., 881: 1–18 **(18 pages).**

Osobamiro, T.M.; Oladipo, A., (2022). Adsorption Study of Paracetamol with Graphene oxide Synthesized from Agricultural waste. Ann. Sci. Technol., 7: 69-75 **(7 pages).**

Özgan, Ş.; Eskalen, H., (2020). Electrical properties of the octyl cyanobiphenyl nematic liquid crystal dispersed with graphene oxide. J. Mater. Sci. Mater. Electron., 31: 19787–19796 **(10 pages).**

Pouretedal, H.R.; Sadegh, N., (2014). Effective removal of amoxicillin, cephalexin, tetracycline and penicillin g from aqueous solutions using activated carbon nanoparticles prepared from vine wood. J. Water Process Eng., 1: 64-73 **(10 pages).**

Samimi, M.; Safari, M., (2022). TMU-24 (Zn-based MOF) as an advance and recyclable adsorbent for the efficient removal of eosin B: Characterization, equilibrium, and thermodynamic studies. Environ. Prog. Sustain. Energy, 41(5): e13859 **(9 pages).**

Samimi, M.; Shahriari-Moghadam, M., (2021). Isolation and identification of Delftia lacustris Strain-MS3 as a novel and efficient adsorbent for lead biosorption: Kinetics and thermodynamic studies, optimization of operating variables. Biochem. Eng. J., 173: 108091 **(9 pages).**

Samimi, M.; Shahriari-Moghadam, M., (2023). The Lantana camara L. stem biomass as an inexpensive and efficient biosorbent for the adsorptive removal of malachite green from aquatic environments: kinetics, equilibrium and thermodynamic studies. Int. J. Phytoremediation, 25(10): 1328-1336 **(9 pages).**

Samimi, M.; Zakeri, M.; Alobaid, F.; Aghel, B., (2023). A Brief Review of Recent Results in Arsenic Adsorption Process from Aquatic Environments by Metal-Organic Frameworks: Classification Based on Kinetics, Isotherms and Thermodynamics Behaviors. nanomaterials, 13(1): 60 **(12 pages).**

Samimi, M.; Mansouri, E., (2023). Efficiency evaluation of Falcaria vulgaris biomass in Co(II) uptake from aquatic environments: characteristics, kinetics and optimization of operational variables. Int. J. Phytoremediation, 1-11 **(11 pages).**

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Santamaría-Juárez, G.; Gómez-Barojas, E.; Quiroga-González, E.; Sánchez-Mora, E.; Quintana-Ruiz, M.; Santamaría-Juárez, J.D., (2019). Safer modified Hummers' method for the synthesis of graphene oxide with high quality and high yield. Mater. Res. Express. 6: 1-10 **(10 pages).**

Tang, Y.; Guo, H.; Xiao, L.; Yu, S.; Gao, N.; Wang, Y., (2013). Synthesis of reduced graphene oxide/magnetite composites and investigation of their adsorption performance of fluoroquinolone antibiotics. Colloids Surf. A., 424: 74–80 **(7 pages).**

Tohamy, H.A.S.; Anis, B.; Youssef, M.A.; Abdallah, A.E.M.; El-Sakhawy, M.; Kamel, S., (2020). Preparation of eco-friendly graphene oxide from agricultural wastes for water treatment. Desalin. Water Treat., 191: 250–262 **(13 pages).**

Wakejo, W.K.; Meshasha, B.T.; Kang, J.W.; Chebude, Y., (2022). Enhanced ciprofloxacin removal from aqueous solution using a chemically modified biochar derived from bamboo sawdust: adsorption process optimization with response surface methodology. Adsorpt. Sci. Technol., 2022: 1–23 **(23 pages).**

Wang, P.; Liu, H.; Guo, H.; Yu, Y.; Guo, Y.; Yue, G.; Li, Q.; Wang, L., (2023). Study on preparation and performance of alkali-activated low carbon recycled concrete: corn cob biomass aggregate. J. Mater. Res. Technol., 23: 90–105 **(16 pages).**

Yadav, S.; Goel, N.; Kumar, V.; Tikoo, K.; Singhal, S., (2018). Removal of fluoroquinolone from aqueous solution using graphene oxide: experimental and computational elucidation. Environ. Sci. Pollut. Res. Int., 25: 2942–2957 **(16 pages).**

Yu, F.; Sun, S.; Han, S.; Zheng, J.; Ma, J., (2016). Adsorption removal of ciprofloxacin by multi-walled carbon nanotubes with different oxygen contents from aqueous solutions. Chem. Eng. J., 285: 588–595 **(8 pages).**

Yusof, A.M.; Malek, N.A.N.N., (2009). Removal of Cr(IV) and As(V) from aqueous solution by HDMTA-modified zeolite Y. J. Hazard. Mater., 162: 1019–1024 **(6 pages).**

Zhang, W.; Ma, Y.; Santos-López, I.A.; Lownsbury, J.M.; Yu, H.; Liu, W.G.; Truhlar, D.G.; Campbell, C.T.; Vilches, O.E., (2017). Energetics of van der waals adsorption on the metal-organic framework NU-1000 with Zr6-oxo, hydroxo, and aqua nodes. J. Am. Chem. Soc., 140: 328–338 **(11 pages).**

Zhu, G.; Cheng, G.; Wang, P.; Li, W.; Wang, Y.; Fan, J., (2019). Water compatible imprinted polymer prepared in water for selective solid phase extraction and determination of ciprofloxacin in real samples. Talanta., 200: 307–315 **(9 pages).**

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CASE STUDY

Clean and healthy environmental behavior in terms of malnutrition and sanitation

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ABSTRACT

BACKGROUND AND OBJECTIVES: A lousy environment has the potential to be a predictor of disease transmission, which ultimately results in malnutrition among children. Meanwhile, the mother's role is crucial in the first 1000 days of life. This research aimed to determine the determinants of maternal behavior in preventing chronic malnutrition in children on the basis of environmental aspects.

METHODS: This cross-sectional study with a quantitative design was conducted in Surabaya, Indonesia, with a sample of 208 pregnant women and 222 mothers of toddlers. A questionnaire was used to identify information related to the dependent variable, chronic malnutritional prevention behavior, on the basis of environmental aspects, and independent variables related to the determinants of maternal behavior. Data were analyzed via Chi-square test using the Statistical Program for Social Sciences.

FINDINGS: As many as 80.8 percent of pregnant women and 65.8 percent of mothers under five had good chronic malnutritionchronic malnutrition prevention behavior. The perception of behavioral control in using clean water is significantly related to the behavior of pregnant women and mothers of toddlers, with significance values of 0.012 and 0.013, respectively. The perceived behavioral control towards washing hands with soap has a significant relationship with the behavior of pregnant women and mothers of toddlers, with significance values of 0.003 and 0.005, respectively. Pregnant women with poor behavioral control in washing their hands with clean water and soap were 2.963 times more likely to have poor chronic malnutritionchronic malnutritional prevention behavior than the comparison group. Subjective norms of using clean water and washing hands with clean water and soap in pregnant women are significantly related to chronic malnutritionchronic malnutrition prevention behavior, with significance values of 0.011 and 0.049, respectively, and odds ratios of 2 and 2.280, respectively.

CONCLUSION: Environment-based chronic malnutritionchronic malnutritional prevention behavior in mothers is primarily influenced by perceived behavioral control and subjective norms. The family can be part of the subjective norms that drive aspects of attitudes and perceptions of behavioral control related to environment-based chronic malnutritionchronic malnutrition prevention practices. Meanwhile, the aspects of controlling maternal behavior can be intervened through efforts to minimize obstacles and increase the perception of benefits from behavior to prevent chronic malnutrition. Maternal behavioral change interventions could encourage the implementation of good behavior in preventing malnutrition in children. In the end, children could learn the behavior given by their mothers and adopt it.

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INTRODUCTION

The problem of malnutrition in children is not only related to food availability or access but also driven by environmental sanitation aspects (Oginawati *et al.,* 2023). Environmental factors indirectly influence children's growth and development (Yenita *et al*., 2021), which can ultimately lead to poor nutritional status in children (Ainy *et al.,* 2021). In Indonesia, environmental factors that threaten children come from exposure to contaminated water, air, food, and soil (Haryanto, 2020). These sources of exposure indicate the importance of implementing hygiene and sanitation. Good environmental sanitation can reduce the potential for a history of infectious diseases in children (Bliznashka *et al*., 2021). In Indonesia, the proportion of households with access to adequate sanitation services reached 80.92 percent (%) in 2022. This percentage increased by 0.63% compared with that in 2021 (BPSRI, 2022). Environmental sanitation factors include water, sanitation, and hygiene (WASH), which is a factor that explains most (24.0%) of the difference in the incidence of chronic malnutrition in children living in urban and rural areas. Poor WASH access and behavior causes 1.6 million deaths annually (Chirgwin *et al*., 2021), and it is a determinant of chronic malnutrition in children (Lin *et al*., 2023). The incidence of malnutrition becomes more frequent in low-income families. Low-income family environmental sanitation increases the potential for children to experience chronic malnutritionchronic malnutrition 1.979 times compared with children from families with good sanitation (Oginawati *et al*., 2023). Healthy environmental sanitation needs to be continuously maintained by involving families (Ainy *et al*., 2021). Good environmental sanitation can reduce the potential for a history of infectious diseases in children (Bliznashka *et al*., 2021). Efforts to avoid chronic malnutritionchronic malnutrition can be made in the first 1000 days of life, which is a critical period for children's growth and development (Shirisha *et al.,* 2022). In the first 1000 days of a child's life, the child's body is in a dynamic stage of body development, so it is vulnerable to exposure to environmental factors. Exposure to these four sources can increase the risk of potential diseases, such as acute hepatitis A, diarrhea, dengue fever, and malaria, due to lack of water supply and sanitation, vectors, parasites, and others (Haryanto, 2020; Truong *et al.,* 2023). Infectious diseases can have implications for poor nutritional conditions in children. When a child suffers from an infectious disease, the child's appetite becomes poor. The absorption of nutrients into the child's body becomes less than optimal. Disturbances in food intake and insufficient supply of essential substances needed by the body can result in weight loss among children, resulting in nutritional and energy intake that is less than what the child should need. In the long term, infection with infectious diseases can encourage child malnutrition due to decreased appetite and absorption of nutrients in the intestine (Fadjriah *et al*., 2021). The most significant proportion of children's nutritional problems is chronic malnutritionchronic malnutrition (Lefebo *et al*., 2023). Chronic malnutritionChronic malnutrition is a failure in a child's anthropometry, resulting in a disproportionate body due to weight loss (Li *et al*., 2020). In 2019, Indonesia experienced a decrease in the proportion of chronic malnutritionchronic malnutrition from 27.7% to 24.4% in 2021. However, the decrease in the proportion of chronic malnutritionchronic malnutrition is inversely proportional to the number of provinces where the prevalence rate is higher than the national average. In 2019, 17 provinces had prevalence rates higher than the national prevalence rate. In 2021, 19 provinces had a prevalence above the national prevalence (Wulandari *et al*., 2022). The accumulation of these conditions places Indonesia in fourth place, with the highest incidence of children with chronic malnutrition globally. The spread of this deformation could affect the Indonesian economy. Clean and healthy living behavior/Perilaku Hidup Bersih dan Sehat (PHBS) is a public health improvement program that was launched in 1996. The application of PHBS indicators can provide short- and long-term positive effects. However, 27 years after the PHBS program was launched, its implementation remains far from expectations. Basic health research in Indonesia, carried out every 5 years, reported its latest findings in 2018 that only 39.1% of households implemented PHBS (Kementerian Kesehatan, 2020a). Risk factors for stunted child growth, which leads to malnutrition, are infections during pregnancy, teenage mothers (too young), poor parenting patterns, working mothers, and mothers exposed to cigarette smoke during pregnancy (Kementerian Kesehatan, 2020b). In other words, the mother is the key that comes from outside the child, related to the potential for malnutrition in children. Prevention of chronic malnutrition in children depends on the mother's behavior in fulfilling children's nutrition (Pedro *et al.,* 2022). The productive, reproductive, and social roles of pregnant women and toddler mothers are very strategic, and they determine the nutritional status of children (Yenita *et al.,* 2021). Maternal behavior is supported by knowledge regarding factors that influence malnutrition status in children. However, in previous research, the knowledge of mothers, especially pregnant women, was lacking and one of the causes of chronic child malnutrition in Indonesia (Li *et al*., 2020). Environmental sanitation is part of the benchmark for implementing PHBS. Various cultural, social, and economic prohibitions become challenges in implementing PHBS. Meanwhile, one of the causes of chronic malnutrition in Indonesia is the mother's poor perception regarding preventing chronic malnutritionchronic malnutrition in children (Siswati *et al*., 2022), which reflects maternal behavior. In this case, environment-based PHBS indicators are a form of chronic malnutritionchronic malnutrition prevention behavior. Previous research focused on epidemiological analysis using clean water and washing hands with soap on poor nutritional status in children (Gaffan *et al*., 2023), biological impacts (Hendricks *et al.* 2022), determinants based on nutritional provision, and exclusive breastfeeding (Zeleke *et al*., 2022). Meanwhile, studies focusing on behavioral determinants of preventing unequal nutritional status in children still need to be improved, especially those focusing on environmental relationships. The present study, which was conducted in Surabaya, Indonesia, in 2022, aimed to explore maternal behavior while detailing each sanitation practice associated with chronic malnutritional prevention behavior.

MATERIALS AND METHODS

This study is a cross-sectional study. The population consisted of mothers related to the first 1000 days of a child's life, namely, pregnant women and mothers of toddlers. Previous research generally focused on child characteristics (Gizem, 2023) and mother characteristics without distinguishing between pregnant women and toddler mothers (Singh *et al.,* 2023). Meanwhile, the present study focuses on mothers. They were differentiated into two groups: pregnant women and mothers of toddlers. These two groups are closely related to the first 1000 days of a child's life, so the behavior of these two groups of mothers can represent the results of identifying determinants of preventing chronic malnutrition in children. The two groups of mothers were further divided to determine their chronic malnutrition prevention behavior, which may be similar or different. Thus, identifying each group of mothers could indicate appropriate interventions for both groups. This study was conducted in Surabaya, the capital of East Java Province, which is a province that administratively oversees 29 districts and nine cities (Fig. 1). Surabaya was chosen as the location for this study because of its massive chronic malnutrition phenomenon. In 2020, the local government recorded that more than 12,000 children under five experienced chronic malnutrition.

Data collection and sample size

During the study, respondents agreed to participate by signing a consent form. Respondents answered questions accompanied by research assistants in that field of study. Structured questionnaires and interviews were used to collect accurate data regarding demographic data, chronic malnutritional prevention behavior based on environmental aspects, and behavioral determinants based on theory of planned behavior (TPB). Maternal characteristics are essential in preventing child malnutrition (Hossain *et al*., 2022). Demographic data includes age, education, employment status, maternal characteristics based on babies or toddlers, and number of children. TPB consists of three groups: attitudes, perceived behavioral control, and subjective norms for each environment-based PHBS element (Table 1).

Respondents' opinions regarding chronic malnutrition prevention behavior based on environmental aspects gave 4 points for "yes, I have done it for more than six months," 3 for "yes, I have done it but less than six months," 2 for "yes, I have done it but less than six months," 1 for "no, but I plan to do it in the next 30 days," and 0 for "no and I do not plan to do it in the next six months." Respondents' opinions regarding attitudes were measured using a 5-point Likert scale with the range of 1 (never), 2 (rarely), 3 (sametimes), 4 (often), and 5 (always). An example of an attitude statement in the questionnaire is as follows: "I consider that not using clean water for daily activities is dangerous for my

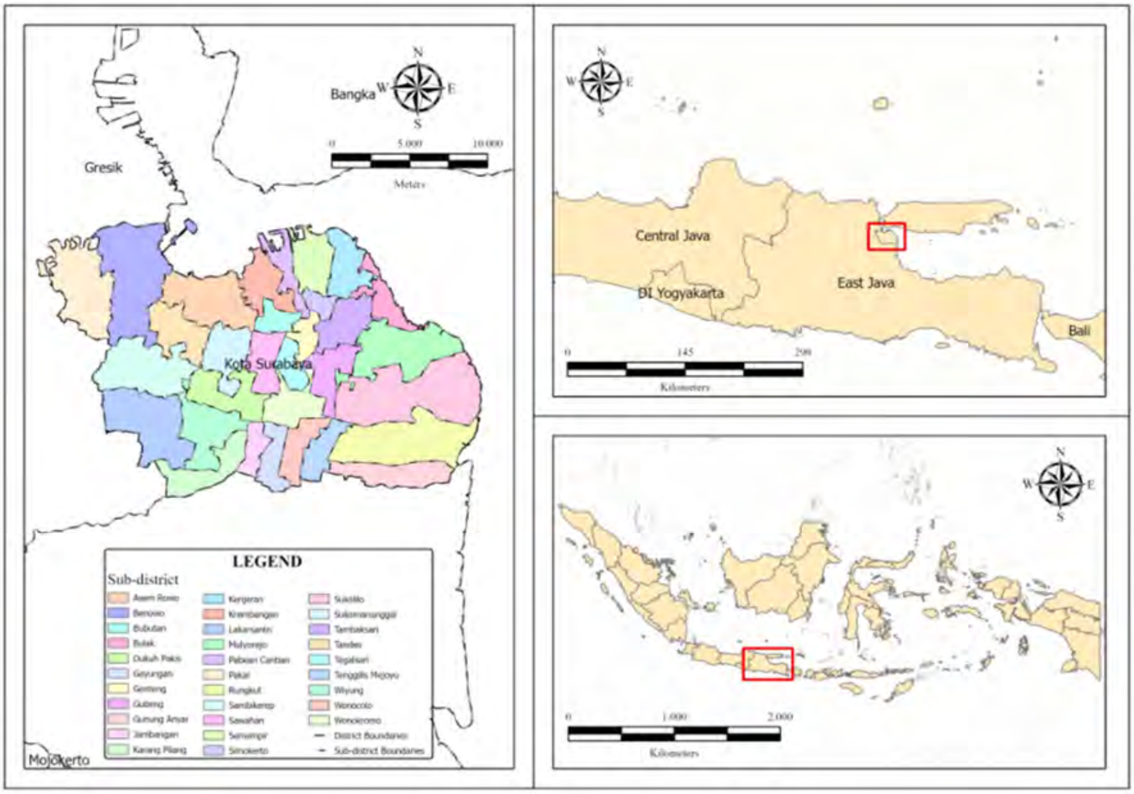

Fig. 1: Geographic location of the study area in Surabaya, East Java, Indonesia

children and me." A Likert scale with the range of 1 (not tempted at all), 2 (not tempted enough), 3 (quite tempted), 4 (tempted), and 5 (very tempted) was also used to identify perceived behavior. An example of a statement of perceived behavioral control in the questionnaire is as follows: "I feel tempted not to use clean water because I am in an environment that does not support me to use clean water." Respondents' subjective norms were described using a Likert scale with the range of 1 (not important), 2 (slightly important), 3 (quite important), 4 (important), and 5 (very important). An example of a subjective norm statement in the questionnaire is as follows: "Using clean water for daily activities will be a hassle for my family." A sample of 208 pregnant women and 222 mothers of toddlers was randomly selected as respondents.

Data analysis

Data were analyzed using SPSS. The dependent variable is chronic preventive behavior that is based on environmental aspects. The independent variables are attitude towards the use of clean water, attitude towards washing hands with soap and clean water, perceived behavioral control towards the use of clean water, perceived behavioral control towards washing hands with soap and clean water, subjective norms towards the use of clean water, and subjective norms against washing hands with soap and clean water. Univariate analysis was used to explain the demographic features of the respondents (age, occupation, education, and total number of children). Chronic malnutrition awareness were analyzed, and the number of respondents with behavioral response categories of good and poor was compared. Bivariate data between the dependent variable (chronic malnutritional prevention behavior based on environmental aspects) of mothers under five and pregnant women on environment-based PHBS indicators were analyzed on the basis of three aspects of TPB. Bivariate analysis was conducted using Chi-square test to show which factors significantly

Table 1: Study questionnaire

Question	Answer
Respondent identity	
Age	In year
Education	Middle/junior high school, senior high school, diploma, bachelors, no answer
Occupation	Not working, working, no answer
Total number of children	1,2,3,4,5, or 6 children
Chronic malnutritional prevention behavior based on environmental aspects	
Do you use clean water in your daily household activities? (e.g. washing, cooking, bathing)	Yes, I have been doing it for over 6 months; yes, I have done it but for less than 6 months; no, but I plan to do it in the next 30 days; no, but I plan to do it in the next 6 months; no and I do not plan to do so in the next 6 months
Do you wash your hands using soap and clean water?	Yes, I have been doing it for over 6 months; yes, I have done it but for less than 6 months; no, but I plan to do it in the next 30 days; no, but I plan to do it in the next 6 months; no and I do not plan to do so in the next 6 months
Attitudes (behavioral believes and outcome evaluations)	
Utilize clean water (20 questions)	Never, rarely, sometimes, often, always
Wash hands with clean wáter and soap (20 questions)	Never, rarely, sometimes, often, always
Perceived behavioral control (control ideas and their influence)	
Not utilizing clean wáter (9 questions)	Not tempted at all, not tempted enough, quite tempted, tempted, very tempted
Not washing hands with clean wáter and soap (9 questions)	Not tempted at all, not tempted enough, quite tempted, tempted, very tempted
Subjective norms (normative beliefs and motivation to comply)	
Utilizing clean water behavior (6 questions)	Not important, slightly important, quite important, important, very important
Washing hands with clean water and behavior soap (6 questions)	Not important, slightly important, quite important, important, very important

differed, with a statistical significance level at a p-value > 0.05.

RESULTS AND DISCUSSION

As shown in Table 2, the respondents consisted of 208 pregnant women, with an average age of 25 years and 8 months. The average age of mothers of toddlers is around 29 years and 9 months. This study aligns with previous research, which had an average age of mothers of 29.53 ± 2.92 years (17–45 years) (Yeganeh *et al.*, 2023). Maternal age is related to the possibility of child nutrition. Children of mothers aged 20–25 years are 4.3 times more likely to not pay special attention to child nutrition than mothers aged 30 years (Getu *et al.,* 2023). Malnutrition is more common in children whose mothers are under 18 years old (Hossain *et al.,* 2022). Most pregnant women (124 people, 59.6%) had high school education (52%) and work. Meanwhile, 131 mothers of toddlers (59%) had high school education, and 112 (50.5%) did not work. This study aligns with that of Yeganeh *et al.* (2023), who found that most mothers (41%) had a high school diploma. A higher education indicated 1.329 times better feeding behavior in mothers (Akbar *et al.*, 2022). Mothers' working status can be considered in looking at mothers' level of awareness regarding the prevention of chronic malnutrition in children. Non-working mothers have a higher probability of having malnourished children by 3.31 times than working mothers (Shahid *et al.*, 2022). Shahid *et al.* (2022) research looked into the implications of mothers' work on family income. Even though her employment status, mothers can also have implications for the time they can devote to implementing chronic malnutritional prevention behavior, mainly those based on environment. A total of 168 pregnant women (80.8%) had awareness about good chronic malnutrition, and 146 mothers were under five (65.8%). Another characteristic factor is the total number of children in the household. Mothers under five predominantly have one child, namely 92 mothers under five (41.4%). This study aligns with Yeganeh *et al*. (2023), who found an average number of children of 1.77 ± 0.78 (range of 1–6 children). The number of children can indicate aspects of the mother's experience and attention to the number of children in the household.

Kementerian Kesehatan (2020b) explains that the risk factors for malnutrition in children come from the mother and the child. Factors in children include low-birth-weight babies, child's difficulty drinking breast milk from the mother, suffering from infections (acute or chronic), congenital births, introducing solid foods too late or too early, and inadequate feeding. Meanwhile, maternal factors are infections during pregnancy, teenage mothers, poor parenting patterns, mothers exposed to cigarette smoke during pregnancy, and working mothers (Fig. 2). Previous research stated that malnutrition is prevented through providing breast milk, colostrum, and complementary foods (Forth *et al.,* 2022). In particular, giving complementary foods to breast milk is related to the mother's ability to prepare these foods hygienically. Hygienic preparation of complementary breast milk foods can prevent exposure to infectious diseases and malnutrition in children aged 6–24 months. One indicator of the hygienic preparation of complementary foods for breast milk is the household water source (Zeleke *et al*., 2022). Water is the most basic need for all living creatures, including humans (Moghadam and Samimi, 2022). However, human activities cause an increase in the burden of air pollution (Abidin, 2023), which could ultimately become a vehicle for infectious diseases. Chronic malnutrition prevention behavior includes improving sanitation and implementing handwashing with soap to reduce the risk of further transmission and recurrent infections (Wulandari *et al*., 2022). These two behaviors are preventive efforts in the environment-based PHBS concept. The first two years of life are crucial for implementing chronic malnutritional prevention interventions in children (Woldesenvent *et al.,* 2023).

Chronic malnutritional events early in life result in growth disorders that are directly proportional to functional disorders of the child's body. In other words, chronic undernutrition affects cognitive abilities and affects education, productivity, and employment. Babies aged 0–6 months who experience chronic malnutrition and are still experiencing chronic malnutrition at the age of 7–8 years have a 2.8 times greater risk of experiencing decreased cognitive

Table 2: Respondent demographic characteristics

Variables	Pregnant women		Women with a child (under 5 years young)	
	n	%	n	%
Age	208	(25.8 ± 5.08)	222	(29.9 ± 4.9)
Education				
Middle/junior high school	6	2.9	11	5
Senior high school	108	52	131	59
Diploma	21	10	10	4.5
Bachelors	73	35.1	70	31.5
Occupation				
Not working	84	40.4	112	50.5
Working	124	59.6	110	49.5
Total number of children				
1	-	-	92	41.4
2			84	37.8
3			35	15.8
4			9	4.1
5			1	0.5
6			1	0.5
Chronic malnutritional prevention behavior based on environmental aspects				
Poor	40	19.2	76	34.2
Good	168	80.8	146	65.8

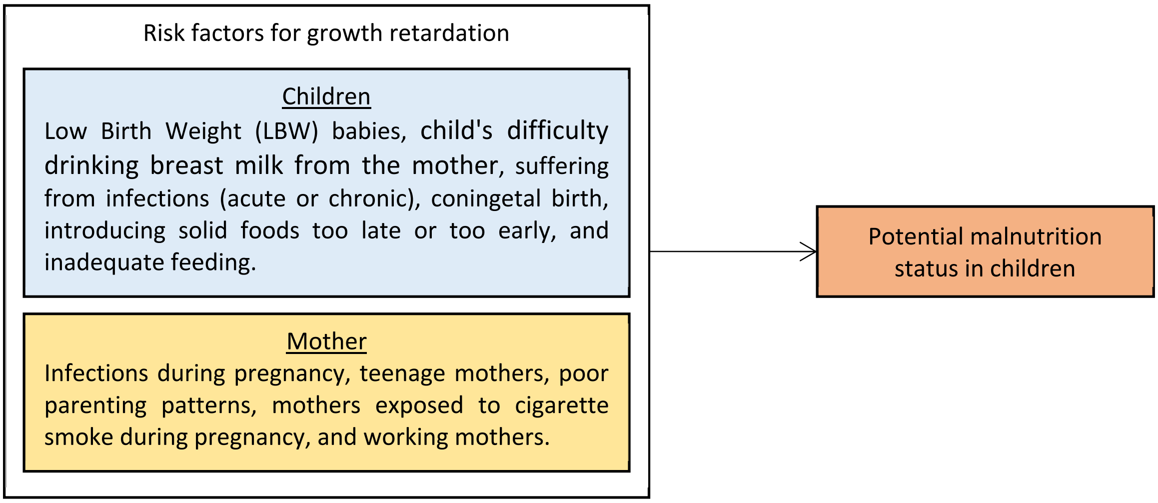

Fig. 2: Potential malnutrition status in children (Kementerian Kesehatan, 2020b)

function than babies who do not experience chronic malnutrition. David Barker's research began in the 1980s in England by comparing affluent and low-income countries with the prediction that the risk factor for noncommunicable diseases is lifestyle, which is related to economic conditions. Barker stated that rich countries have a higher prevalence of heart disease than low-income countries. However, data obtained in the field showed a different phenomenon. Low-income countries have a higher prevalence of heart disease than rich countries. Therefore, Barker concluded that noncommunicable diseases are not only caused by economic conditions but also past factors that influence the genetic conditions that humans carry from the beginning of life and develop with the encouragement of environmental factors (Barker, 2012). Using clean water is the first environmental factor that can influence children's nutritional status.

Table 3 shows that 105 mothers did not have good attitudes, although 83 (79%) had good chronic malnutrition prevention behavior. Meanwhile, 103 respondents had good attitudes towards using clean water, of which 85 pregnant women (85.5%) had good chronic malnutrition prevention behavior. Pregnant women's attitudes towards the use of clean water were not significantly related to chronic malnutritional prevention behavior (p-value = 0.525). Perceived behavioral control over the use of clean water in pregnant women was related to chronic malnutritional prevention behavior, with a significant p-value of 0.012. A total of 110 pregnant women experienced behavioral control related to inappropriate use of clean water. Ninety-six pregnant women (87.3%) knew about good chronic malnutrition. Meanwhile, 98 people (86.7%) had the perception of behavioral control related to good clean water, and 78 people (86.7%) had good chronic malnutrition prevention behavior. Pregnant women with the perception of not having good behavioral control regarding the use of clean water had 2.476 times the potential to have poor chronic malnutrition prevention behavior compared with pregnant women with good behavioral control. Meanwhile, the subjective norm aspect of clean water use had a significant relationship (p-value = 0.011). Pregnant women without good subjective norms regarding the use of clean water were two times more likely to not carry out good chronic malnutrition prevention behavior than pregnant women with good subjective norms. Meanwhile, the environmental-based prevention of chronic malnutrition in children included washing hands with clean water and soap. Most of the attitudes of pregnant women in washing their hands by using clean water and soap were poor. A total of 118 pregnant women did not have good attitudes, of which 76.3% (118 pregnant women) had good chronic malnutrition prevention behavior. The

Table 3: Results of Chi-square analysis in pregnant women

Variable	Chronic malnutritional prevention behavior based on environmental aspects				Total	OR (95% CI)	p-value
	Poor		Good				
	n	%	n	%			
Attitudes (behavioral believes and outcome evaluations)							
Utilize clean water							
Poor	22	21	83	79	105	1.252	0.525
Good	18	17.5	85	85.5	103	(0.626–2.502)	
Wash hands with clean water and soap							
Poor	28	23.7	90	76.3	118	2.022	0.059
Good	12	13.3	78	86.7	90	(0.964–4.243)	
Perceived behavioral control (control ideas and their influence)							
Utilize clean water							
Poor	26	26.5	72	73.5	98	2.476	0.012*
Good	14	12.7	96	87.3	110	(0.197–0.828)	
Wash hands with clean water and soap							
Poor	28	27.4	74	72.6	102	2.963	
Good	12	11.3	94	88.7	106	(0.161–0.708)	0.003**
Subjective norms (normative beliefs and motivation to comply)							
Utilize clean water							
Poor	32	22.2	112	77.8	144	2.000	0.011*
Good	8	12.5	56	87.5	64	(0.865–4.626)	
Wash hands with clean water and soap							
Poor	32	23	107	77	139	2.280	
Good	8	11.5	61	88.5	69	(0.988–5.262)	0.049*

attitude of washing hands with clean water and soap was good in 90 pregnant women, of which 78 (86.7%) had good chronic malnutrition prevention behavior. The second TPB aspect analyzed was the perception of control behavior regarding the use of clean water and washing hands with clean water and soap. The perceived behavioral control regarding washing hands with clean water and soap showed a significant relationship with the behavior to prevent chronic malnutrition in pregnant women (p-value = 0.003). Pregnant women whose perception of behavioral control was poor in terms of washing their hands with clean water and soap had 2.963 times the potential to have poor chronic malnutrition prevention behavior compared with pregnant women whose perception of behavioral control was good. The number of mothers who perceived good and poor behavioral control was almost the same at 106 and 102, respectively. Most pregnant women (94, 88.7%) perceived that they do not have good behavioral control and good chronic malnutritional prevention behavior. The subjective norms regarding washing hands with clean water and soap for pregnant women were significantly related to children's chronic malnutritional awareness (p-value = 0.049). Pregnant women with poor subjective norms regarding washing with clean water were 2.280 times more likely to not carry out good chronic malnutrition prevention behavior than pregnant women with good subjective norms. Regarding frequency, 139 pregnant women had subjective norms regarding washing their hands with clean water and soap, and 107 people (77%) did not have good chronic malnutrition prevention behavior (Table 3).

Chronic malnutrition or linear growth disorders involve a complex interaction of genetic, family, environmental, socioeconomic, and cultural influences. Clean environmental sanitation and PHBS practices support the success of family health (Fadjriah *et al*., 2021). Previous research stated that the behavior of washing hands with soap and using clean water is the primary determinant in preventing chronic malnutrition (Lin *et al*., 2023). Based on Table 4, the attitudes of mothers of toddlers regarding the use of clean water were not related to chronic malnutritional prevention behavior (p-value = 0.917). One hundred fifteen mothers of toddlers did not have good attitudes towards using clean water, whereas 107 had good attitudes. Thirty-nine mothers of toddlers (33.9%) did not have good chronic malnutritional prevention behavior nor good attitude towards using clean water. The attitudes towards washing hands with soap among mothers of toddlers were not significantly related to chronic malnutritional prevention behavior (p-value = 0.840). One hundred sixteen mothers of toddlers had no good attitudes towards washing their hands with clean water and soap, whereas 106 had good attitudes. Mothers of toddlers (77, 66.4%) predominantly had no good attitudes towards handwashing with soap and good chronic malnutritional prevention behavior. Two environment-based clean living behaviors in perceived behavioral control were found to be significant for chronic malnutritional prevention behavior. Perceived behavioral control in using clean water had a p-value of 0.013. Mothers of toddlers with no good perceived behavioral control regarding the use of clean water were 2.027 times more likely to have poor chronic malnutritional prevention behavior than mothers of toddlers with good perceived behavioral control. Most mothers of toddlers (87, 73.1%) had good perceived behavioral control regarding the use of clean water and good chronic malnutritional prevention behavior. Meanwhile, the perceived behavioral control related to washing hands with clean water and chronic malnutritional prevention behavior exhibited a p-value of 0.005. Mothers of toddlers with no good perceived behavioral control regarding washing their hands with clean water were 2.207 times more likely to have poor chronic malnutritional prevention behavior than mothers of toddlers with good perceived behavioral control. Most mothers of toddlers (83, 74.8%) had good perceived behavioral control regarding washing hands with clean water and good chronic malnutritional prevention behavior. Previous research on mothers' exclusive breastfeeding behavior showed that their behavioral control influences their perceived benefits. Awareness of these benefits can be encouraged through nutrition education programs that educate children about breast milk's benefits. The knowledge that mothers of toddlers gain could reflect what the mother feels (Rachmah *et al.,* 2023). Meanwhile, research in Africa suggested that perceived behavioral control is related to barriers experienced by mothers, such as limited resources and income, lack of knowledge, and time constraints for working mothers (Anyango *et al.,* 2021). Thus, preparing intervention formulations that could strengthen the perceived benefits and find solutions to obstacles is essential to encourage the perception of maternal behavioral control in a good direction in implementing behavior to prevent malnutrition in children. The subjective norms in environment-based PHBS were not significantly related to chronic malnutrition awareness of mothers of toddlers. The relationship between subjective norms regarding the use of clean water for mothers of under 5 years old and chronic malnutritional prevention behavior had a p-value of 0.566. As many as 114 mothers of toddlers had subjective norms related to poor use of clean water, whereas 77 (67.6%) had good chronic malnutritional prevention behavior. By contrast, 108 mothers of toddlers had subjective norms regarding using good clean water, and 69 (63.9%) had good chronic malnutrition awareness. The relationship between subjective norms related to washing hands with clean water and soap and chronic malnutritional prevention behavior had a p-value of 0.129. A total of 115 mothers of toddlers did not have good subjective norms regarding washing hands with clean water and soap, and 81 (70.4%) had good chronic malnutrition awareness. By contrast, 107 mothers of toddlers had subjective norms regarding washing their hands with clean water and good soap, and 65 (60.7%) had good chronic malnutrition awareness (Table 4). The availability of sanitation facilities is the primary determinant of the incidence of chronic malnutrition in children (Saheed *et al*., 2022). Malnutrition in children under 5 years old is a public health problem in low-income countries (Sufri *et al.,* 2023). Most of the world's poor, especially in rural areas, do not have access to safe drinking water (Mulyaningsih *et al*., 2023) and basic sanitation or handwashing facilities (Hasan *et al*., 2023). More than half of children (55.3%) live in households without access to basic sanitation facilities, and almost two out of every three (62.6%) children live without access to washing facilities that offer soap and pure water (Hasan *et al*., 2023). Children from families that do not have access to clean water and sanitation are 1.27 times more likely to suffer from chronic malnutrition than children from households with access to clean water and sanitation (Gaffan *et al*., 2023). Previous research found that access to tap water at home does not guarantee access to clean water. Water often does

Table 4: Results of Chi-square analysis on mothers of toddlers

Variable	Chronic malnutritional prevention behavior based on environmental aspects				Total	OR (95% CI)	p-value
	Poor		Good				
	n	%	n	%			
Attitudes (behavioral believes and outcome evaluations)							
Utilize clean water							
Poor	39	33.9	76	66.1	115	0.971	0.917
Good	37	34.6	70	65.4	107	(0.557–0.1691)	
Wash hands with clean water and soap							
Poor	39	33.6	77	66.4	116	0.945	0.840
Good	37	34.9	69	65.1	106	(0.542–1.645)	
Perceived behavioral control (control ideas and their influence)							
Utilize clean water							
Poor	44	42.7	59	57.3	103	2.027	0.013*
Good	32	26.9	87	73.1	119	(0.281–0.866)	
Utilize clean water							
Poor	48	43.2	63	56.8	111	2.207	0.005*
Good	28	25.2	83	74.8	111	(0.250–0.783)	
Subjective norms (normative beliefs and motivation to comply)							
Utilize clean water							
Poor	37	32.4	77	67.6	114	0.850	0.566
Good	39	36.1	69	63.9	108	(0.488–1.481)	
Utilize clean water							
Poor	34	29.6	81	70.4	115	0.650	0.129
Good	42	39.3	65	60.7	107	(0.372–1.135)	

not flow to residents' homes. Thus, the tap water supply is considered unable to meet the residents' clean water needs. Moreover, processing tap water, which is generally boiled first, is considered to be another obstacle. The process of boiling water incurs additional costs for purchasing fuel (Dickson-Gomez *et al.,* 2023). Other research added that changes in the prevalence of malnutrition in an area are influenced by access to piped water. Enhanced access to piped water could reduce the prevalence of malnutrition. Thus, stakeholders must collaborate in a multisectoral manner to ensure accessibility of factors that could increase the prevalence of malnutrition, including access to clean water (Brar *et al*., 2020). Based on the Republic of Indonesia Government Regulation Number 185 of 2014, the central, provincial, and district governments must accelerate public infrastructure development to ensure all residents have access to safe drinking water, sanitation, and cleanliness. This investment significantly improves children's health and reduces chronic malnutrition in Indonesia (Mulyaningsih *et al*., 2023). In addition, additional costs are an obstacle to washing hands with soap and clean water (Watson *et al*., 2023). Consistent and effective WASH behavioral practices are urgently needed to improve children's health in low-income areas with difficult hygiene conditions (Meierhofer *et al*., 2023). Meanwhile, facilities for basic hygiene, such as soap for washing hands, have a significant effect. Children who come from households that do not have basic hygiene facilities are 1.33 times more likely to be underweight (Gaffan *et al*., 2023). Using clean water and washing hands with soap and clean water can mediate 23.96% of the difference in chronic malnutrition incidence between urban and rural areas. Children from households with poor WASH behavior have a higher risk of experiencing chronic malnutrition, with a crude relative risk of 2.19 (Lin *et al*., 2023). Sanitation is an essential factor in reducing the number of illnesses and deaths due to nutritional problems, such as those caused by diarrhea in low-income areas (Hendricks *et al.,* 2022). Diarrhea is an infectious disease that can affect the incidence of chronic malnutrition. It is the leading cause of child morbidity and mortality, and it is directly related to chronic malnutrition in early childhood (Wolf *et al.,* 2023). Diarrhea causes the deaths of around 525,000 children every year. Chronic diarrhea places children at risk of cognitive deficits, less-than-optimal performance at school, and reduced immunity into adulthood. Bad behavior in using clean water and not washing hands with soap is the main determining factor in diarrhea through contamination from unclean water (Dickson-Gomez *et al.,* 2023). One of the bacteria that causes diarrhea is *Shigella*, the second leading cause of diarrheal morbidity and mortality in children in low- and middle-income countries. Poor sanitation is one of the risk factors for *Shigella*. Children with good sanitation can reduce the risk of *Shigella* incidence by 98.85% compared with children from families with poor sanitation (Rogawski *et al*., 2020). Other research found that washing hands with soap and using clean water is significantly associated with *Giardia lamblia* infection, fever, coughing, and chronic malnutrition in children. The frequency of washing hands with soap significantly reduces the odds ratio (OR) for the potential incidence of *G. lamblia* infection, fever, and chronic malnutrition. Meanwhile, using clean containers as an intermediary between the water source and the water storage location is essential. Using clean containers to transport drinking water significantly reduces the OR of *G. lamblia* infection (Meierhofer *et al.,* 2023), which can trigger chronic malnutrition. In other research, mothers play an important role in determining the determinants of chronic malnutrition behavior. Previous research found that children whose mothers do not wash their hands before feeding their children are a critical factor in chronic malnutrition children aged 24–59 months. These findings are based on mothers washing their hands after defecating, cleaning the baby's anus, and breastfeeding the child (Woldesenvent *et al.,* 2023). This finding relates to other factors related to chronic malnutrition, making it important to formulate nutrition promotion and disease prevention interventions at the community level (Mshida *et al.,* 2018). For maternal and fetal nutrition to be met, providing health education or promotion regarding pregnancy health is necessary, which can be performed via telephone (Konyole *et al.,* 2023). The Indian state provides an example of health promotion related to maternal and child nutrition through the Mobile Solutions Aiding Knowledge for Health Improvement (M-SAKHI) program to assist health workers in providing education about pregnancy health to pregnant women and their families (Ogutu *et al.,* 2022). Furthermore, clean living habits need to be applied to children for them to get used to living cleanly, from teaching children to wash their hands before and after eating and before carrying out daily activities to teaching children to fulfill their defecation needs at home toilets (Nurjazuli *et al*., 2023). Other driving factors include social norms involving family members and lack of knowledge about the health effects on children (Parveen *et al*., 2018). Access to WASH facilities with enhanced quality can help children survive and thrive (Hasan *et al.,* 2023). Environmental sanitation and personal hygiene programs must be strengthened (Woldesenvent *et al*., 2023). WASH must be considered a system, and various improvements are needed to function (Dickson-Gomez *et al.,* 2023). Coordination between relevant institutions to overcome these two factors is needed to reduce and prevent chronic malnutrition effectively (Sufri *et al.,* 2023). Equalizing perceptions regarding factors related to poor nutritional status in children based on using clean water and washing hands with soap is essential. The same perception can facilitate the design of appropriate interventions to encourage the implementation of good behavior in preventing malnutrition among children. The relationship between factors that influence poor nutritional status in children is explained on the basis of the results of the present study and those of previous research in Fig. 3.

The mother's attitude in using clean water and washing hands with clean water and soap is critical in reducing the incidence of chronic malnutrition in children. Another study found that simply washing hands with clean water and soap did not reduce the incidence of chronic malnutrition in children in low-income countries (Humphrey *et al*., 2019). Previous research found that the source of obstacles to implementing cleanliness habits was piped water access to resident's homes (Yunitasari *et al*., 2022). Interventions can be carried out by conveying health promotion messages through household visits and group meetings. Interventions through health promotion programs can be designed on the basis of the risk, attitudes, norms, abilities, and self-regulation (RANAS) behavior change model. This health promotion program intervenes with mothers by providing tools and materials regarding

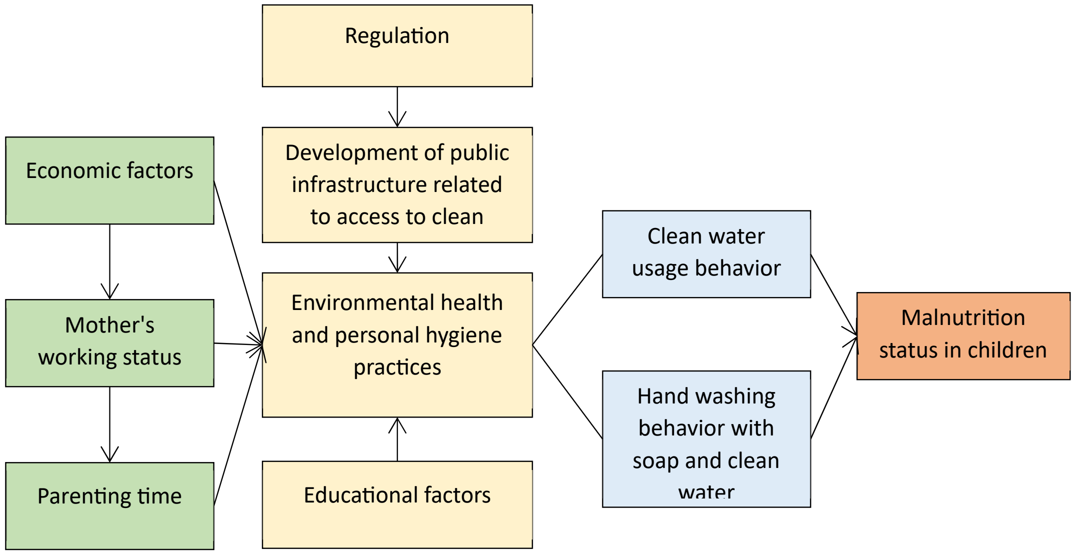

Fig. 3: Relationship between determinants of malnutrition in children based on environmental health and personal hygiene practices

malnutrition prevention behavior. It can provide behavioral support facilities, such as soap for washing hands. Health activists use local languages to convey information to mothers effectively. This program also provides bracelets for mothers containing short messages inviting them to wash their hands with soap (Panulo *et al*., 2022). Thus, health promotion program interventions include efforts to provide not only information to targets but also items they need to behave well, such as soap. However, providing goods is an effort to encourage trial behavior in mothers. So, mothers' behavioral abilities depend on the results of the assessment of their experimental behavior. Therefore, designing an action plan that includes regular training for Posyandu cadres is essential to increase knowledge and skills regarding chronic malnutrition in children. Action can be taken by starting regular campaigns to improve WASH practices and providing adequate facilities to prevent children from experiencing chronic malnutrition (Sufri *et al.,* 2023). The government must be able to educate mothers through health workers at the Community Health Center (Puskesmas), Community Health Center (Puskesmas), Posyandu, or other affairs.

CONCLUSION

Awareness about chronic malnutrition in both groups of mothers was predominantly good. However, behavioral factors based on TPB showed that they were still less dominant. The attitudinal aspect of using clean water and washing hands with soap was not significantly related to pregnant women's chronic malnutrition prevention behavior, with significance values 0.525 and 0.059, respectively. Meanwhile, the two environment-based chronic malnutrition prevention factors were related to chronic malnutrition prevention behavior in perceived behavioral control and subjective norms. Pregnant women with poor perceived behavioral control regarding the use of clean water had 2.476 times more significant potential to have poor chronic malnutritional prevention behavior. Pregnant women without good perceived behavioral control regarding washing their hands with clean water had 2963 times more significant potential to have poor chronic malnutritional prevention behavior. Pregnant women with unfavorable subjective norms regarding the use of clean water had two times more significant potential to have poor chronic malnutritional prevention behavior. Pregnant women with poor subjective norms regarding washing hands with clean water and soap had 2.280 times more significant potential to have poor chronic malnutritional prevention behavior. Meanwhile, for mothers of toddlers, a significant relationship was found in the perceived behavioral control aspect of using clean water and washing hands with clean water and soap only, with significance values of 0.013 and 0.005, respectively. Mothers of toddlers without good subjective norms regarding washing hands with clean water and soap had 2.207 times more significant potential to have poor chronic malnutritional prevention behavior. Mothers of toddlers with unfavorable subjective norms regarding using clean water and soap had 2.027 times more significant potential to have poor chronic malnutritional prevention behavior. The factors that made these two groups of mothers have different results in identifying behavioral determinants are worthy of further analysis. The two groups tended to come from different demographic groups. In addition, the status of pregnant women may be related to cultural rules that tend to apply and bind mothers during pregnancy. These rules can generally influence maternal behavior through subjective norm aspects. In addition, this study recognizes the limitations of a research design that only focuses on behavioral aspects by using closed questions. Future research could explore the awareness of chronic malnutrition and maternal behavior more deeply through in-depth interviews and focus group discussions. Socioeconomic and cultural factors that encourage the application of PHBS indicators in these two groups must be studied. This study demonstrated the need to increase maternal awareness and behavior in preventing chronic malnutrition through environment-based PHBS practices. The government and multisectors must be able to carry out collaborative interventions in educating mothers through the closest health services in the community to strengthen mothers' awareness of preventing chronic malnutrition in all aspects of behavior formation, including beliefs, motivation, and perceived behavioral control.

AUTHOR CONTRIBUTIONS

E. Parahyanti was the corresponding author, supervising the study, obtaining funding, and conceptualization. Nuraeni participated in writing the original draft, reviewing and editing, preparing pictures and tables of study results, and drawing conclusions. N.I. Hawa participated in data analysis and interpretation. D. Utari participated in the investigation, methodology, and resource preparation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
>	More than
<	Less than
≥	More than or equal to
–	Until
±	Plus/minus

BPSRI	Badan Pusat Statitik Republik Indonesia
LBW	Low Birth Weight
M-SAKHI	Mobile Solutions Aiding Knowledge for Health Improvement
MGRS	Multicenter growth reference study
OR	Odd ratio
p-value	Probability value
PHBS	Perilaku Hidup Bersih dan Ssehat (Clean and healthy living behavior)
Posyandu	Pos Pelayanan Terpadu (integrated service post)
Puskesmas	Pusat Kesehatan Masyarakat (Community Health Center Community Health Center)
RANAS	Risk, attitudes, norms, abilities, and self-regulation
RI	Republic Indonesia
RR	Relative risk
SD	Standard deviation
SPSS	Statistical package for the social science
TPB	Theory of planned behavior
WASH	Water, sanitation, and hygiene
WHO	World Health Organization

REFERENCES

Abidin, J.Z., (2023). Challenges in dealing with water pollution issues in the West Java island. J. Sustainabilty Soc. Eco-Walfare., 1(1): 31-48 **(18 Pages).**

Ainy, F.; Susanto, T.; Susumaningrum, L., (2021). The relationship between environmental sanitation of family and stunting among under-five children: A cross-sectional study in the public health center of Jember, Indonesia. Nurs. Pract. Today. 8(3): 1-6 **(6 pages).**

Akbar, M.; Asif, A.M.; Hussain, F., (2022). Does maternal empowerment improve dietary diversity of children? evidence from Pakistan demographic and health survey 2017–18. Int. J. Health Plann. Manage.,37(6): 3297-3311 **(15 pages).**

Barker, D.J.P., (2012). Developmental origins of chronic disease. Public Health. 126(3): 185–189 **(5 pages)**.

Bliznashka, L.; Udo, I.E.; Sudfeld, C.R.; Fawzi, W.W.; Yousafzai, A.K., (2021). Associations between women's empowerment and child development, growth, and nurturing care practices in sub-Saharan Africa: A cross-sectional analysis of demographic and health survey data. PLoS Med., 18: e1003781 **(30 pages)**.

BPSRI, (2022). Persentase Rumah Tangga menurut Provinsi dan Memiliki Akses terhadap Sanitasi Layak (Persen), 2020-2022.

Brar, S.; Akseer, N.; Sall, M.; Conway, K.; Diouf, I.; Everett, K.; Islam, M.; Sène, P.I.S.; Tasic, H.; Wigle, J.; Bhutta, Z., (2020). Drivers of stunting reduction in Senegal: a country case study. Am. J. Clin. Nutr., 112: 860S-874S **(15 pages)**.

Chirgwin, H.; Cairncross, S.; Zehra, D.; Sharma; Waddington, H., (2021). Interventions promoting uptake of water, sanitation and hygiene (WASH) technologies in low- and middle-income countries: An evidence and gap map of effectiveness studies. Campbell Syst. Rev., 17: e21194 **(79 pages).**

Dickson-Gomez, J.; Nyabigambo, A.; Rudd, A.; Ssentongo, J.; Kiconco, A.; Mayega, (2023). Water, Sanitation, and Hygiene Challenges in Informal Settlements in Kampala, Uganda: A Qualitative Study. Int. J. Environ. Res. Public Health. 20(12): 6181 **(13 pages).**

Fadjriah, R.N.; Rusdianto, R.; Herman, H.; Vidyanto, V., (2021). Factors associated with the stunting in toddlers in the work area of tikson raya public health center. Open Access Macedonian J. Med. Sci., 9(E): 1207–1212 **(6 pages)**.

Gaffan, N.; Kpozehouen, A.; Degbey, C.; Ahanhanzo, Y.G.; Paraiso, M.N., (2023). Effects of the level of household access to water, sanitation and hygiene on the nutritional status of children under five, Benin. BMC Nutr., 9: 95 **(12 pages).**

Getu, B.D.; Azanaw, K.A.; Zimamu, L.Y.; Adal, G.M., (2023). Wasting and its associated factors among children aged from 6 to 59 months in Debre Tabor town, Amhara region of Ethiopia, 2019: a multicentre community-based cross-sectional study. BMJ Open. 13: e071679 **(7 pages).**

Haryanto, B., (2020). Indonesia: country report on children's environmental health. Rev. Environ. Health. 35(1): 41–48 **(8 pages)**.

Hasan, M.M.; Asif, C.A.A.; Barua, A.; Banerjee, A.; Kalam, M.A.; Kader, A.; Wahed, T.; Noman, M.W.; Talukder, A., (2023). Association of access to water, sanitation and handwashing facilities with undernutrition of children below 5 years of age in Bangladesh: evidence from two population-based, nationally representative surveys. BMJ Open. 13(6): e065330 **(10 pages).**

Hendricks, M.K.; Sambo, M.; Laubscher, R.; Pendlebury, S.; Bourne, L., (2022). Determinants of diarrhoeal disease in children living in low-income households in a periurban community in Cape Town, South Africa. S. Afr. J. Child Health, 16(3): 165 **(8 pages).**

Hossain, M.M.; Abdulla, F.; Rahman, A., (2022) Prevalence and determinants of wasting of under-5 children in Bangladesh: Quantile regression approach. PLoS One. 17(11): e0278097 **(16 pages).**

Humphrey, J.H.; Mbuya, M.N.N.; Ntozini, R.; Moulton, L.H.; Stoltzfus, R.J.; Tavengwa, N.V.; Mutasa, K.; Majo, F.; Mutasa, B.; Mangwadu, G.; Chasokela, C.M.; Chigumira, A.; Chasekwa, B.; Smith, L.E.; Tielsch, J.M.; Jones, A.D.; Manges, A.R.; Maluccio, J.A.; Prendergast, A.J.; Makoni, T., (2019). Independent and combined effects of improved water, sanitation, and hygiene, and improved complementary feeding, on child stunting and anaemia in rural Zimbabwe: a cluster-randomised trial. The Lancet Global Health. 7(1): e132–e147 **(16 pages)**.

Kementerian Kesehatan R.I., (2020a). Peraturan Menteri Kesehatan Republik Indonesia Nomor 2 Tahun 2020 tentang Standar Antropometri Anak. Kementerian Kesehatan RI, Jakarta **(8 pages).**

Kementerian Kesehatan, R.I., (2020b). Pencegahan dan tata laksana gizi buruku pada balita di layanan rawat jalan bagi tenaga kesehatan. Kementerian Kesehatan RI, Jakarta **(250 pages).**

Konyole, S.O.; Omollo, S.A.; Kinyuru, J.N.; Owuor, B.O.; Estambale, B.B.; Ritz, C.; Michaelsen, K.F.; Filteau, S.M.; Wells, J.C.; Roos, N.; Friis, H.; Owino, V.O.; Grenov, B., (2023). Associations between stunting, wasting, and body composition: A longitudinal study in 6- to 15-month-old Kenyan children. J. Nut., 153(4): 970-978 **(9 pages).**

Lefebo, B.K.; Kassa, D.H.; Tarekegn, B.G., (2023). Factors associated with stunting: gut inflammation and child and maternal-related contributors among under-five children in Hawassa City, Sidama Region, Ethiopia. BMC Nutr., 9(1): 54 **(8 pages)**.

Li, Z.; Kim, R.; Vollmer, S.; Subramanian, S.V., (2020). Factors Associated With Child Stunting, Wasting, and Underweight in 35 Low- and Middle-Income Countries. JAMA Netw. Open. 3(4): e203386 **(18 pages)**.

Lin, J.; Feng, X.L., (2023).). Exploring the impact of water, sanitation and hygiene (WASH), early adequate feeding and access to health care on urban–rural disparities of child malnutrition in China. Mate. Child Nutr., 19: e13542 **(12 pages).**

Meierhofer, R.; Kunwar, B.M.; Shrestha, A., (2023). Changes in water treatment, hygiene practices, household floors, and child health in times of Covid-19: A longitudinal cross-sectional survey in Surkhet District, Nepal. Int. J. Hyg. Environ. Health. 249(2023): 114138 **(14 pages).**

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages).**

Mshida, H.A.; Kassim, N.; Mpolya, E.; Kimanya, M., (2018). Water, Sanitation, and Hygiene Practices Associated with Nutritional Status of Under-Five Children in Semi-Pastoral Communities Tanzania. Am. J. Trop. Med. Hyg., 98(5): 1242–1249 **(8 pages)**.

Mulyaningsih, T.; Mohanty, I.; Gebremedhin, T.A.; Miranti, R.; Widyaningsih, V., (2023). Does access to water, sanitation, and hygiene improve children's health? An empirical analysis in Indonesia. Dev. Policy Rev., 41: e12706 **(25 pages)**.

Nurjazuli, N.; Budiyono, B.; Raharjo, M.; Wahyuningsih, N.E., (2023). Environmental factors related to children diagnosed with stunting 3 years ago in Salatiga City, Central Java, Indonesia. Toxicol. Anal. Clin., 15(3): 198-205 **(8 pages).**

Oginawati, K.; Yapfrine, S.J.; Fahimah, N.; Salami, I.R.S.; Susetyo, S.H., (2023). The associations of heavy metals exposure in water sources to the risk of stunting cases. Emerging Contam., 9(4): 100247 **(8 pages).**

Ogutu, E.A.; Ellis, A.; Rodriguez, K.C.; Caruso, B.A.; McClintic, E.E.; Ventura, S.G.; Arriola, K.R.J.; Kowalski, A.J.; Linabarger, M.; Wodnik, B.K.; Webb-Girard, A.; Muga, R.; Freeman, M.C., (2022). Determinants of food preparation and hygiene practices among caregivers of children under two in Western Kenya: a formative research study. BMC Public Health. 22: 18656 **(18 pages)**.

Panulo, M.; Chidziwisano, K.; Beattie, T.K.; Tilley, E.; Kambala, C.; Morse, T., (2022). Process Evaluation of "The Hygienic Family" Intervention: A Community-Based Water, Sanitation, and Hygiene Project in Rural Malawi. Int. J. Environ. Res. Public Health. 19: 6771 **(19 pages).**

Parveen, S.; Nasreen, S.; Allen, J.V.; Kamm, K.B.; Khan, S.; Akter, S.; Lopa, T.M.; Zaman, K.; Arifeen, S.E.; Uby, S.P.; Ram, S.K., (2018). Barriers to and motivators of handwashing behavior among mothers of neonates in rural Bangladesh. BMC Public Health. 18: 483 **(13 pages).**

Pedro, A.; Batweni, Z.; Bradfield, L.; Dare, M.; Nyman, A.; Petersen, C.A.L.; Truskey, K.M., (2022). First 1000 days: first-time mothers' understanding and experiences of nutritional care. Early Child Dev. Care., 192(10): 1561–1569 **(9 pages).**

Rachmah, Q.; Astina, J.; Atmaka, D.R.; Khairani, L., (2023). The Effect of Educational Intervention Based on Theory of Planned Behavior Approach on Complementary Feeding: A Randomized Controlled Trial. Int. J. Pediatr., 2023: 1086919 **(11 pages).**

Rogawski, M.E.T.; Shaheen, F.; Kabir, F.; Rizvi, A.; Platts-Mills, J.A.; Aziz, F.; Kalam, A.; Qureshi, A.; Elwood, S.; Liu, J.; Lima, A.M.M.; Kang, G.; Bessong, P.; Samie, A.; Hague, R.; Mduma, E.R.; Kosek, M.N.; Shresta, S.; Leite, J.P.; Bodhidatta, L.; Page, N.; Kiwelu, I.; Shakoor, S.; Turab, A.; Soofi, S.B.; Ahmed, T.; Houpt, E.R.; Bhutta, Z.; Iqbal, N.T., (2020). Epidemiology of Shigella infections and diarrhea in the first two years of life using culture-independent diagnostics in 8 low-resource settings. PLOS Neglec. Trop. Dis., 14(8): e0008536 **(17 pages)**.

Saheed, R.; Shahid, M.; Wang, J.; Qureshi, M.G.; Sun, X.; Bibi, A.; Zia, S.; Tang, K., (2022). Impact of Drinking Water Source and Sanitation Facility on Malnutrition Prevalence in Children under Three: A Gender-Disaggregated Analysis Using PDHS 2017–18. Children. 9: 1674 **(12 pages).**

Shahid, M.; Cao, Y.; Ahmed, F.; Raza, S.; Guo, J.; Malik, N.I.; Rauf, U.; Qureshi, M.G.; Saheed, R.; Maryam, R., (2022). Does Mothers' Awareness of Health and Nutrition Matter? A Case Study of Child Malnutrition in Marginalized Rural Community of Punjab, Pakistan. Front. Public Health. 10 **(11 pages).**

Shirisha, P.; Muraleedharan, V.R.; Vaidyanathan, G., (2022). Wealth related inequality in women and children malnutrition in the state of Chhattisgarh and Tamil Nadu. BMC Nutr., 8: 86 **(21 pages)**.

Shrestha, A.; Schindler, C.; Odermatt, P.; Gerold, J.; Erismann, S.; Sharma, S.; Koju, R.; Utzinger, J.; Cissé, G., (2020). Nutritional and health status of children 15 months after integrated school garden, nutrition, and water, sanitation and hygiene interventions: A cluster-randomised controlled trial in Nepal. BMC Public Health. 20(1), 1–19 **(19 pages)**.

Singh, S.; Shri, N.; Singh, A., (2023) Inequalities in the prevalence of double burden of malnutrition among mother–child dyads in India. Sci Rep, 13: 16923 **(13 pages).**

Siswati, T.; Iskandar, S.; Pramestuti, N.; Raharjo, J.; Rubaya, A.K.; Wiratama, B.S., (2022). Drivers of Stunting Reduction in Yogyakarta, Indonesia: A Case Study. Int. J. Environ. Res. Public Health, 19: 16497 **(14 pages)**.

Sufri, S.; Nurhasanah; Jannah, M.; Dewi, T.P.; Sirasa, F.; Bakri, S., (2023). Child Stunting Reduction in Aceh Province: Challenges and a Way Ahead. Mater. Child Health J., 27: 888-901 **(4 pages).**

Truong, T.H.; Nguyen, L.T.T.; Nguyen, D.D.; Pham, T.; Vu, T.M.; Nguyen, P.H.; Nguyen, Q.T., (2023). Water security assessment framework for the deltas of the transboundary river basins. Global J. Environ. Sci. Manage., 9(3): 619-636 **(18 pages).**

Watson, J.; Amon-Tanoh, M.A.; Deola, C.; Haji, M.A.; Sheikh, M.R.; Mohamud, F.A.; Ali, S.Y.; MacDougall, A.; Cumming, O., (2023). Effect of a novel hygiene intervention on older children's handwashing in a humanitarian setting in Kahda district, Somalia: A cluster-randomised controlled equivalence trial. Int. J. Hyg. Environ. Health. 250: 114613 **(9 pages).**

Woldesenbet, B.; Tolcha, A.; Tsegaye, B., (2023). Water, hygiene and sanitation practices are associated with stunting among children of age 24-59 months in Lemo district, South Ethiopia, in 2021: community based cross sectional study. BMC Nutr., 9: 17 **(19 pages).**

Wolf, J.; Johnston, R.B.; Ambelu, A.; Arnold, B.F.; Bain, R.; Brauer, M.; Brown, J.; Caruso, B.A.; Clasen, T.; Colford Jr, J.M.; Mills, J.E.; Evans, B.; Freeman, M.C.; Gordon, B.; Kang, G.; Lanata, C.F.; Medlicott, K.O.; Prüss-Ustün, A.; Troeger, C.; Boisson, S.; Cumming, O., (2023). Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. The Lancet. 401(10393): 2060-2071 **(12 pages).**

Wulandari, R.D.; Laksono, A.D.; Kusrini, I.; Tahangnacca, M., (2022). The Targets for Stunting Prevention Policies in Papua, Indonesia: What Mothers' Characteristics Matter? Nutrients. 14(3): 549 **(10 pages)**.

Yeganeh, S.; Motamed, N.; Boushehri, S.N.; Bagherzadeh, R.; Ravanipour, M., (2023). Evaluation of maternal performance about food security in dietary diversity for children aged 12-24 months and its relationship with anthropometric measurements. BMC Pediatr, 23: 256 **(8 pages)**.

Yenita, R.N.; Thamrin, T.; Amin, B.; Agrina, A., (2021). Identification and analysis of stunting risk factors in children under three years of age in the area of kampar watershed. Open Access Maced. J. Med. Sci., 9: 149–157 **(9 pages).**

Yunitasari, E.; Lee, B.O.; Krisnana, I.; Lugina, R.; Solikhah, F.K.; Aditya, R.S., (2022). Determining the Factors That Influence Stunting during Pandemic in Rural Indonesia: A Mixed Method. Children, 9: 1189 **(16 pages)**.

Zeleke, A.M.; Bayeh, G.M.; Azene, Z.N., (2022). Hygienic practice during complementary food preparation and associated factors among mothers of children aged 6–24 months in Debark town, northwest Ethiopia, 2021: An overlooked opportunity in the nutrition and health sectors. PLoS One, 17(12): e0275730 **(17 pages).**

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ORIGINAL RESEARCH ARTICLE

Evaluation of community behavior regarding the risk of plastic micro-pollution on the environment health

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ABSTRACT

BACKGROUND AND OBJECTIVES: Plastic pollution is increasing globally along with the growing consumption patterns of the global community, leading to practicality (social behavior). The primary contributors to pollution are single-use plastic (SUP) items and inadequate waste management techniques. This research attempts to examine local communities' determinants and behavioral patterns regarding plastic waste management.

METHODS: This cross-sectional analytical study includes 195 respondents and conducted at Antang Lake, Makassar. The social sciences statistical package version 26 was used to perform chi-square tests and multiple regression analysis to examine the main elements influencing individual behavior toward plastic waste management. A survey instrument was provided to participants for data collection.

FINDINGS: The chi-square test results show that the knowledge variable has a statistically significant relationship with plastic waste management behavior at home, with a test statistical value of 0.002. Respondents with limited knowledge are 2.603 times more likely to have poor household plastic waste management behavior than those with substantial knowledge. The knowledge variable is also significantly related to household plastic waste management behavior simultaneously with a statistical test value of 0.000, showing a strong relationship. This variable influences 11.8 percent of the behavior in question. Attitude and action variables do not have a significant relationship partially or simultaneously with household plastic waste management behavior.

CONCLUSION: Increased plastic consumption has led to microplastic pollution, environmental damage, and deteriorating health conditions. Thus, intervention is required to improve optimal waste management behavior in the community. Increasing awareness about environmental management and educating the public on the impact of microplastics on family health can contribute to enhanced knowledge awareness. This research aims encourage greater awareness of environmental condition to minimize toxicity resulting from the negative impacts of plastic waste.

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INTRODUCTION

Plastic is a versatile material that can be processed using various manufacturing techniques and has huge market potential. Polymer chains of monomers are combined in repeating patterns to form plastic (Choudhury *et al*., 2022). More than 50 percent (%) of existing plastic is single-use plastic (SUP) and is one of the main components of solid waste (Jahani *et al*., 2019). People's daily behavioral patterns become increasingly, contributing to the growing plastic use worldwide. This circumstance is driven by the widespread use of SUP for daily requirements by a large number of people worldwide. This situation promotes post-use plastic pollution in the form of goods and SUP sachets, accompanied by inadequate waste management practices in several regions worldwide (Yang *et al*., 2022). Society plays a direct role in creating demand for SUP. People's perceptions and desires greatly influence people's behavior (Van Rensburg *et al.,* 2020). Post-pandemic plastic waste mishandling has increased rapidly and caused serious environmental impacts because of the ineffectiveness and inadequacy of the current waste management system and the lack of enforcement of environmental regulations (Raja *et al.,* 2020). Amid various human pressures on aquatic ecosystems, the accumulation of plastic waste is one of the most evident but least studied (Mihai *et al*., 2021). Several studies have shown that plastic additives, such as Bisphenol A (BPA) and phthalates, can cause adverse effects on human reproduction and growth, including carcinogenesis. In addition, microplastics contaminated with harmful chemicals can accumulate in the human body by consuming seafood and polluted drinking water (Katyal *et al*., 2020). The non-biodegradability of plastic, unsustainable usage, presence of heavy metal content, and inappropriate waste management have led to extensive accumulation of plastic in natural habitats (Kumar *et al*., 2021). The microplastics (MPs) can be detected in aquatic environments due to the degradation processes (Stead and Bond, 2023). This phenomenon gives rise to detrimental consequences concerning the environment and human well-being (Okunola *et al.,* 2019). Plastics of various sizes, classes, and origins are found in aquatic environments (rivers, lakes, and seas) (Anderson *et al*., 2016). The impacts of plastic waste are evident in several countries, including Asuncion Bay, Paraguay (Diez-Pérez *et al.,* 2023), China (Chen *et al*., 2023), and Ireland (Devereux *et al*., 2023). MPs can be detected in various maritime ecosystems (Guzzetti *et al.,* 2018), particularly in areas characterized by substantial human influence (Cordova *et al*., 2022). MPs are plastic particles that measure less than 5 millimeters (mm) in size. These particles can be introduced into the environment through sources, such as personal care products, activities, and the breakdown of larger plastic items (Buwono *et al*., 2022). These fragments, composed of plastic materials, pose significant challenges within marine ecosystems (Yuan *et al*., 2023). Aggregated MPs tend to sink to the sea floor, potentially becoming accessible to benthic populations (Riani and Cordova, 2022). MPs can readily assimilate into biological processes, leading to adverse consequences on aquatic species given their comparable dimensions to the primary food sources of abundant aquatic organisms (Chen *et al*., 2022). A wide range of marine invertebrates, fish, marine reptiles, and marine mammals have been documented as consuming plastic particles of varying sizes (Buwono *et al*., 2022). When fish consume MP particles, the ingestion is often accompanied by the presence of toxins, severely damaging the fish upon ingestion. In addition, the particles have the potential to be transferred and deposited higher up in the food chain. MPs are anticipated to engage with diverse organisms owing to their diminutive dimensions, which can lead to detrimental consequences when consumed in elevated quantities. The potential outcomes can arise either directly through the initiation of oxidative stress and harm or indirectly through increased susceptibility to pollutants, such as absorbed chemicals. MPs may also contribute to decreased population density resulting from biological mortality. The size and shape of MPs affect their interactions with organisms. On the contrary, MPs can promote the activation of natural immune responses and can alter the makeup of microbial communities in the gastrointestinal tract, initiating inflammatory reactions and damage to the gut epithelium (Wu *et al*., 2023). Ocean circulation has a crucial role in the distribution and transport of MPs, a consequence of water pollution issues addressed by MPs. The importance of high-resolution spatial mapping in the understanding of global MP distribution budgets cannot be overstated (Enfrin *et al*., 2019). Numerous studies and authoritative reports affirm that the contamination of marine ecosystems by MPs primarily originates from terrestrial and fluvial sources (Costa *et al.,* 2023). MPs have also emerged as a significant contaminant in the present context, presenting an ecological hazard to surface water ecosystems (Velmurugan *et al.,* 2023). Plastic pollution can cause significant health risks to humans given the ability of microplastics to absorb heavy metals and other dangerous chemicals. Consumption of fish contaminated with microplastics and heavy metals can cause heavy metal poisoning and other health problems. Some health risks associated with exposure to microplastics through fish consumption include oxidative damage to lipids, neurotoxic effects, and human health risks associated with exposure through consumption (Karbassi and Pazoki, 2015). However, in-depth research is still required to fully understand the impact of plastic pollution on health (Sabilillah *et al*., 2023). Plastic waste possesses the capacity to store potentially harmful compounds or chemicals, such as chemical additives, adsorbed chemicals, and unreacted starting ingredients (monomers). These substances fulfill significant roles in plastics and are categorized as antimicrobial agents (biocides), blowing agents, flame retardants, organic dyes, monomers, cross-linkers, hardeners, chain modifiers, catalysts, ultraviolet (UV) stabilizers, antioxidants, plasticizers, solvents, and miscellaneous substances that do not neatly fit into other classifications (Garello *et al.*, 2023). The Irish study considered the impact of the Corona Virus Disease 2019 (Covid-19) pandemic on plastic pollution in the River Thames. The study results showed an increase in MPs during the second lockdown in November 2020, where polyvinyl chloride (PVC) plastic dominated. A decrease in MPs was observed during the first lockdown, but the MP levels have not normalized after the pandemic. The Limehouse site had more MPs during the first lockdown, possibly because the area is densely populated and close to the port (Devereux *et al*., 2023). Indonesia was identified as a prominent contributor to the substantial accumulation of plastic garbage in the world's oceans (Arpia *et al*., 2021). The escalating concern over this issue is attributed to the uncontrolled rise in pollution levels in inland waters, as well as marine and lake habitats, caused by MP contamination (Ali *et al*., 2021). Within various existing research, studies on MP pollution in Indonesian seas and freshwater ecosystems, particularly rivers and lakes, are still relatively new but have garnered increasing interest from various groups (Kumar *et al*., 2021). The comprehensive analysis of the movement patterns of MPs is crucial for gaining insights into their distribution and the factors influencing their abundance. The understanding of the impact of MPs on the operational efficiency of waste water treatment plant (WWTP) processes is closely tied to the assessment of associated operational expenses. The presence of MPs not only hampers the efficiency of the water treatment process but also has a detrimental impact on the quality of treated water. The tactics encompass the application of surface changes to membranes, the utilization of coagulation agents that have been optimized for their effectiveness, and the development of resistance against microbes that may be impacted by the presence of MPs. By implementing these strategies, alleviating any negative impacts exerted by MPs on the overall efficiency of WWTP operations (Enfrin *et al*., 2019). Managing household and industrial wastes involves different challenges and requirements. Household wastes are usually produced in smaller quantities and have more homogeneous properties. Thus, they are easier to collect, separate, and recycle than industrial wastes. Industrial wastes are generally produced in larger quantities and have more complex properties, including various types of hazardous materials and debris, requiring sophisticated technology and infrastructure for their management. Industrial waste management necessitates substantial costs and meticulous planning and supervision to ensure safe generation and disposal of wastes in compliance with applicable environmental regulations and standards (Thanh *et al*., 2011). The novelty of this research lies in the emphasis on innovation and community involvement by focusing on variables, such as knowledge, attitudes, and actions regarding household plastic waste management behavior. Household plastic waste is the main focus because it dominates other types of household waste. Other research includes investigating household waste management practices and perceptions about waste management (Fadhullah *et al*., 2022), river plastic pollution, and its impact on human health (Sabilillah *et al*., 2023). Meanwhile, this research integrates household plastic waste management behavior analysis and determines the negative impact of plastic waste on human and environmental health. The harmful impact of MP waste affects not only human health but also marine ecosystems. People believe that the continually increasing volume of plastic waste will have detrimental effects on livestock. A survey is conducted in this study by observing MP pollution in water areas and its impact on the Makasar water. The innovation resulting from this research intends to determine the household plastic waste management behavior. It also provides innovation for future researchers to explore and further investigate the impact of plastic waste pollution. The government is also expected to provide policies to inform the public about excessive use of plastic. The public is encouraged to participate in preserving the environment by reducing the use of SUP. This study, conducted in Makassar, Indonesia, in 2023, aims to examine the determinants of household plastic waste management behavior by assessing MPs pollution and environmental health.

MATERIALS AND METHODS

This study was conducted at Antang Lake, Makassar City (Fig. 1). Makassar is the capital of South Sulawesi Province, located at Latitude -5.135399 and Latitude 119.423790. The average air temperature in Makassar City ranges from 27 degrees Celsius (°C) to 29.0 °C. The average rainfall is 311 mm, and the average number of rainy days is approximately 17. The study was conducted in August–October 2023. The approach was quantitative study with a cross-sectional research design. A total of 195 respondents were involved in this study with the following inclusion criteria: household heads or other family members who lived around Antang Lake and landfills/ Tempat Pembuangan Akhir (TPA) Antang, Makasar City, Indonesia.

Survey and sample size

During data collection, all respondents agreed to complete the research and document their answers. The total number of respondents in this study was 195. Questionnaires and structured interviews were used to collect accurate data regarding demographics and household plastic waste management behavior based on respondents' knowledge, attitudes, and actions. The behavioral questionnaire consists of

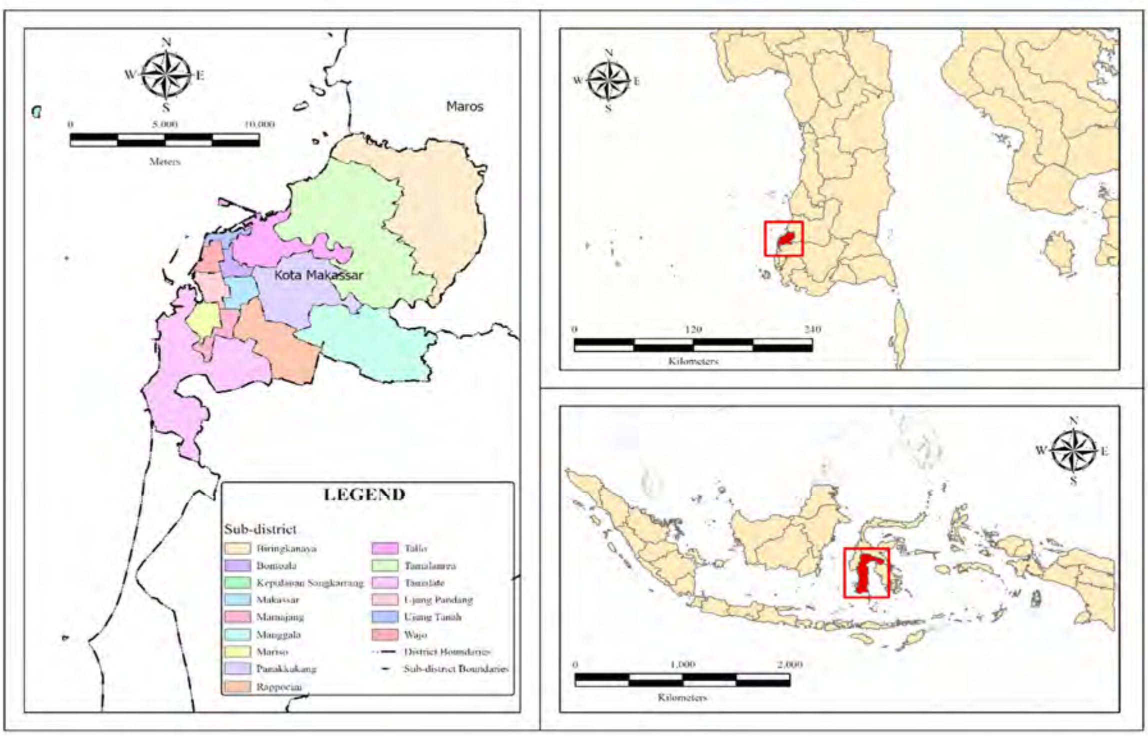

Fig. 1: Geographic location of the study area of Makasar City in Indonesia

19 points, including 14 questions with yes or no answers and five questions with typical simple answers. An example of a behavioral question in the questionnaire is as follows: "Is plastic waste scattered or piled up around your home?" The knowledge questionnaire consists of six questions with typical right and wrong answers. An example of a knowledge question in the questionnaire is as follows: "The ingestion of microplastics through contaminated seafood poses potential risks to human health by introducing harmful substances into the food chain." Six questions were asked to assess the respondents' attitudes, using Likert scale, as follows: strongly agree (SA), agree (A), disagree (D), and strongly disagree (SD). For example, "It is posited that microplastics may provide a potential threat to human health." The questionnaire to evaluate the respondents' actions contain six questions, using Likert scale, as follows: very often (VO), often (O), rarely (RA), and never (N). Tables 1, 2, 3, and 4 show the questionnaires used in the data collection process.

Analysis procedures

During data collection, all respondents agreed to complete the research and document their answers. The data collection stage started with the creation of the inclusion criteria, followed by the actual data collection by the researcher. Subsequently, the researcher performed data encoding in Microsoft Excel to simplify the data processing. Statistical package for the social science (SPSS) version 26 was used for data processing. The univariate approach was applied to examine the frequency and percentage of demographic variables among respondents, including gender, age, marital status, education level, occupation, residency length, and income. The correlation test was performed using the Chi-square analysis technique. This study-dependent variable

Table 1: Household plastic waste management behavior

Questions		Yes	No
1	Is plastic waste scattered or piled up around your home?	125	70
2	Are there lots of flies around the pile of plastic waste?	117	78
3	Are there lots of mice around plastic waste?	126	69
4	Are there many mosquitoes around plastic waste?	150	45
5	Do many animals (cats, dogs, etc.) come to the plastic waste pile?	130	65
6	Is there a disturbing smell around the pile of plastic waste?	86	109
7	Is there a blockage in the drainage channel due to plastic waste?	36	159
8	Did you know that plastic waste can be managed and is beneficial?	149	46
9	Do you manage plastic waste?	45	150
10	Are there any plastic waste management community activities in your area?	16	179
11	Do you take part in plastic waste management activities?	18	177
12	Do you want to take part in plastic waste management activities?	58	137
13	Do you sort plastic waste before throwing it away?	57	138
14	Do you think that rubbish is always collected on time?	131	64

Table 2: Respondent's knowledge

Statement		Correct	Wrong
1	The ingestion of microplastics through contaminated seafood poses potential risks to human health by introducing harmful substances into the food chain.	129	66
2	Microplastics have the potential to infiltrate aquatic ecosystems, hence posing a threat to marine organisms, including fish and other marine fauna.	156	39
3	Microplastics have the potential to cause disruption within aquatic ecosystems and inflict harm upon the species inhabiting them.	143	52
4	It is widely acknowledged that plastic trash has the potential to contaminate and degrade soil quality. So correct them accurately and completely in the right English se	146	49
5	It is widely acknowledged that plastic garbage has the potential to contaminate the atmosphere.	127	68
6	It is widely acknowledged that plastic waste can give rise to many challenges for cattle.	100	95

Table 3: Respondent's attitudes

Statement	SA	A	SD	D
1 There is an opinion that microplastics can potentially threaten human health.	34	127	26	8
2 There are concerns that microplastics may hurt wildlife, including bird species, aquatic organisms, and other fauna.	6	90	81	18
3 It is essential to invite the wider community to actively participate in preserving the lake and surrounding waters by keeping them clean.	12	82	86	15
4 It is essential to practice reusing plastic waste to contribute to environmental sustainability.	8	99	75	13
5 Practicing plastic waste segregation in the home environment and committing to responsible waste management is very important.	7	111	55	22
6 It is essential to implement restrictions or bans on single-use plastics, such as straws, plastic bags, and plastic bottles, which is an essential step in mitigating the problem of microplastic pollution.	39	96	54	6

Table 4: Respondent's actions

Statement	VO	O	R	N
1 Reduce the use of plastic in everyday life.	6	40	119	30
2 Bring a cloth shopping bag when shopping.	6	24	94	71
3 Use metal or paper straws instead of plastic straws	2	25	84	84
4 Learn how to sort and recycle plastic	3	27	75	90
5 Talk to friends and family about the dangers of Microplastics and the importance of reducing plastic consumption and disposing of waste properly	5	17	66	107
6 Collaborate with groups or organizations that care about environmental problems to increase awareness about Microplastics and actions that can be taken to reduce their impact	5	6	50	134

indicates a community behavior toward plastic waste management. The independent variables comprise knowledge, attitudes, and community actions. Researchers provide codes by changing data from sentences or letters into numbers to assist in efficient data processing. The coding in question involves replacing response codes with numbers. The coded data include demographic data, dengue prevention behavior data, knowledge attitude data, social media use data, and social support data. The following hypotheses are put forward in this research:

Hypothesis 1: A relationship exists between knowledge and household plastic waste management behavior.

Hypothesis 2: A relationship exists between attitude and household plastic waste management behavior.

Hypothesis 3: A relationship exists between action and household plastic waste management behavior.

RESULTS AND DISCUSSION

The study sample consisted of 195 individuals, where 170 participants are female. According to Deng *et al.* (2020), gender is significantly related to plastic waste management behavior with a *p*-value of 0.002. The average age of 83 respondents was 26–40, and 175 participants were married. A total of 63 respondents had completed secondary school, and 97 respondents worked as entrepreneurs/traders/services. Previous research suggested that the respondent's educational level is significantly related to plastic waste management behavior, with a *p*-value of 0.001, whereas the age variable is significantly associated with a *p*-value of 0.001 (Fadhullah *et al.*, 2021). Thirty respondents were from the Bangkala sub-district and Manggal sub-district, and most of them (71) were residents for 1–14 years; the income of 93 respondents amounted to USD 48–160 (Table 5).

The results suggest a statistically significant correlation between the knowledge variable and the behavior of household plastic waste management, as indicated by a probability test value (*p*-value) of 0.002 (*p*-value less than (<) 0.05) (Samimi and Moghadam, 2024) (Table 6). These findings indicated that 41 respondents had good knowledge and behavior, whereas 57 respondents had poor knowledge.

Table 5: Respondents Demographic Characteristics (n= 195)

Variable	Frequency	Percentage (%)
Gender		
Male	25	12.8
Female	170	87.2
Age		
<25 years old	24	12.3
26 – 40 years old	83	42.6
41 – 54 years old	53	27.2
55 – 69 years old	30	15.4
>70 years old	5	2.6
Marital Status		
Married	175	89.7
Unmarried	14	7,2
Divorce	2	1
Widowed	4	2.1
Tertiary Education		
Never school	8	4.1
Not graduated from Elementary School	22	11.3
Graduated from Elementary School	40	20.5
Graduated from Junior High School	39	20
Graduated from Senior High School	63	32.3
Graduated from Associate Degree	9	4.6
Graduated from university	14	7.2
Job		
Jobless	2	1
Students/College Students	2	1
Civil Servants/TNI/Polri/BUMN/BUMD	13	6.7
Private employees	17	8.7
Entrepreneur/trader/service	97	49.7
Farmer	2	1
Others	62	31.8
Sub-district		
Antang	25	12.8
Bangkala	30	15.4
Batua	22	11.3
Biring Romang	15	7.7
Bitoa	29	14.9
Borong	15	7.7
Manggala	30	15.4
Tamangapa	29	14.9
Stay length		
1 – 14 years	71	36.4
15 – 29 years	49	25.1
30 – 44 years	44	22.6
45 – 59 years	20	10.3
60 – 74 years	11	5.6
Income		
Rp 4.000.000	20	10.3
Rp 2.500.000 – Rp 4.000.000	62	31.8
Rp 750.000 – Rp 2.500.000	93	47.7
<Rp 750.000	20	10.2

Seventy-six respondents had poor knowledge and behavior in managing household plastic waste. Twenty-one respondents had good knowledge, but had poor behavior in managing household plastic waste. The odds ratio (OR) for the knowledge variable is 2.603, with a 95% confidence level (CI) value in the

Table 6: Chi-square test results of household plastic waste management behavior

Variable	Household plastic waste management behavior				Total	OR (95% CI)	*p-value*
	Poor		Good				
	n	%	n	%			
Knowledge							
Poor	76	57.1	57	42.9	133	2.603	0.002
Good	21	33.9	41	66.1	62	1.389 – 4.879	
Attitude							
Poor	65	54.7	54	45.3	119	1.655	0.088
Good	32	42.1	44	57.9	76	0.926 – 2.959	
Action							
Poor	50	45.8	59	54.2	109	0.703	0.223
Good	47	54.7	39	45.3	86	0.399 – 1.240	

range of 1.389–4.879.

The attitude variable has a *p*-value of 0.088, which is negatively related to household plastic waste management behavior. On the contrary, the OR value is 1.655, with a 95% CI value ranging from 0.926 to 2.959. This finding indicates a relationship between behavior and household plastic waste management. The *p*-value of 0.088 suggests that the observed link does not reach statistical significance when applying the conventional significance level of 0.05. The majority of respondents had terrible attitudes toward household plastic waste management, approximately 65 respondents, and only 44 respondents presented positive attitudes toward household plastic waste management. Lastly, the action variable was also negatively related (*p*-value = 0.223); 50 respondents had poor actions toward household plastic waste management, and only 39 respondents had favorable actions toward household plastic waste management. The OR is 0.703, whereas the 95% CI value ranges from 0.399 to 1.240, indicating a relationship between action and management of household plastic waste. The *p*-value of 0.223 indicates that this relationship is not statistically significant given the commonly used significance level (0.05). The research results in Table 6 show that the knowledge variable is significantly related to household plastic waste management behavior (*p*-value < 0.05). Meanwhile, the attitude and action variables do not affect a person's behavior toward plastic waste management (*p*-value more than (>) 0.05) (Table 6). Based on similar previous research results, only the knowledge variable positively relates to waste management behavior (*p*-value = 0.001) (Zhang *et al*., 2021).

The results of the regression test in Table 7 illustrate that the knowledge variable yielded a *p*-value of 0.000, indicating a statistically significant association between the knowledge variable and plastic waste management behavior. The OR for the knowledge variable is 0.118, suggesting that the knowledge variable has a statistically significant influence of 11.8% on individuals' behavior in the management of plastic garbage. This finding is supported by a 95% Confidence Interval (CI) ranging from 0.071 to 0.165. Moreover, the attitude variable, with a *p*-value of 0.787, and the action variable, with a *p*-value of 0.295, did not demonstrate a statistically significant impact on plastic waste management behavior (*p*-value > 0.05). The correlation coefficient has a correlation coefficient (R) value of 0.356 (or 35.6%). The coefficient of determination has an R square value of 0.127 (or 12.7%). R square is simply the square of R, that is, R times R (Table 8). In a study conducted in Malaysia, several factors had a significant influence on household plastic waste management behavior. These factors include the location of residence (*p*-value < 0.001), age (*p*-value < 0.001), housing type (*p*-value < 0.003), and knowledge (*p*-value < 0.003). The survey participants exhibited a high level of awareness and knowledge regarding appropriate waste management practices, with 92.9% indicating sufficient understanding in this area. The heightened level of consciousness regarding correct waste disposal can be attributed to various factors. The primary determinant is cleanliness, accounting for 81.4% of the motivation. In addition, concerns related to disease prevention contribute to 12.4% of the overall awareness, whereas apprehensions regarding unpleasant odors account for 6.2% of the observed trend (Fadhullah *et al.,* 2022). Table 2 shows that 129

Table 7: Regression análisis

Variable	OR	95% CI	p-value	Explanation
Knowledge	0.118	0.071 – 0.165	0.000	Hypotesis 1 accepted
Attitude	0.006	-0.039 – 0.051	0.787	Hypothesis 2 rejected
Action	-0.023	-0.066 – 0.020	0.295	Hypothesis 3 rejected

Table 8: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.356[a]	.127	.113	.15124

a. Predictors: (Constant), action, knowledge, attituted

respondents stated that that microplastic waste can cause toxicity to human health and living creatures. Moreover, 127 respondents agreed and 34 strongly agreed that microplastic destruction threatens human health. This statement is strengthened by several studies that explain that microplastic waste can cause toxicity to human and environmental health (Yee *et al.*, 2021). Strengthening the results of previous research, the knowledge variable is positively related with a *p*-value of 0.000, indicating that knowledge is significantly associated with household plastic waste management behavior. Variable knowledge of plastic waste on environmental health with a *p*-value of 0.002 (OR 0.221) and knowledge of plastic waste on human health with a *p*-value of 0.010 (OR 0.209) (Deng *et al*., 2020). More focused, detailed, and sustainable awareness and knowledge must be emphasized in this regard, especially on the topics of environmental cleaning, drainage systems, recycling in theory and practice, as well as proper waste disposal (Saat *et al*., 2018). Adequate knowledge, such as clear instructions in communications and collection campaigns, can increase the likelihood of implementing waste sorting behavior (Fadhullah *et al.,* 2022). Some obstacles that prevent waste management from being optimal are ineffective waste management measures, such as dangerous waste dumps, lack of technical knowledge, economic and scientific resources, and a lack of emergency waste processing policies, causing severe consequences for the community and workers (Sarkodie and Owusu, 2021). Plastic becomes MPs through environmental decomposition, including sunlight. This process causes plastic to become brittle, but does not decompose completely. This material is transformed into small pieces called MPs (Rahmawati, 2023). MP pollution from water to the human body, through blood, is classified as a "non-Newtonian" fluid because its viscosity varies with shear rate (Sloop *et al*., 2020). Table 4, showing respondents' actions, indicates that 119 respondents stated that they still rarely reduce the use of plastic in daily life. Another research report suggests that 87.97% of respondents agreed that plastic waste is toxic to human life, and 87.17% of respondents agreed that they would change shopping bags from plastic to environmentally friendly materials (Charitou *et al.,* 2021). Various actions are performed to reduce SUP pollution, including recycling waste, participating in clean-up activities, contributing to environmental campaigns, and throwing plastic waste in the trash. A total of 25.3% of respondents threw plastic waste in the garbage, 24% participated in environmental cleaning activities, and 17% assisted in ecological campaigns. However, 21% of respondents have not taken any action to reduce the use of SUP (Oguge *et al.*, 2021). Research results were conducted by Akdogan *et al.* (2023) by blue particles (25% in water and 18% in sediment). According to the findings of Raman spectroscopic examination, polyethylene terephthalate (PET) constituted 28% and polyamide (PA) constituted 27% of the polymers present in the water sample. Conversely, in the sediment sample, polystyrene (PS) was a dominant polymer, accounting for 56% of the total polymers detected. Contrary to other rivers, the Ergene River exhibits an abundance of several tiers of MPs. A research conducted in Italy using cross-sectional methodology has also indicated a significant and promising decline in pollution at the molecular level, as well as the alleviation of anthropogenic stress. Nevertheless, precise numeric values cannot be assigned to the fluctuations in volatile loads that may be directly linked to specific sources, such as tourist behavior, traffic patterns, urban water systems, and plastic pollution. Consequently, a drop in pollution level was observed; nevertheless, the MPs in Italy still contribute to water contamination (Koumi *et al*., 2021). Diez–Pérez *et al*. (2023) stated that MPs were detected in all of the samples analyzed. The presence of MPs was significantly higher (p-value < 0.05) in water collected from the bay, with an average concentration of 13.2 plus or minus (±) 13.4 items/cubic meter (m^3), compared with water from the tributaries, with an average concentration of 1.0 ± 0.5 items/m^3. Abundant monomeric units, known as MPs, are frequently encountered in the form of polymers. These polymers exhibit varying levels of abundance, with polypropylene being the most prevalent, followed by high-density polyethylene and low-density polyethylene. These polymers can possess transparent or white characteristics. Fig. 2 shows that 155 participants engaged in the daily practice of collecting plastic debris from their households. Another research discussed about the manner of waste disposal, where 84.2% of the respondents use disposal containers near their house. In this study, "smart trash cans" are used in managing plastic wastes optimally. These cans work by collecting waste in containers, optimizing the process of transporting packaging waste from urban containers to sorting plants.

This approach reduces the final cost of recycled plastic through transportation and testing fuel efficiency. Subsequently, in the sorting process, the types of waste collected from the factory are separated per category. The last step is recycling. In the final stage, the development and validation of retail value products from plastic packaging waste are carried out, leading to the stabilization of the cost of recycled materials and creating better outcomes for the market (Cerasi *et al*., 2021). The areas within Teddington exhibited elevated levels of MPs during the Covid-19 pandemic, despite the absence of lockdown measures, compared with the pre-pandemic period. This phenomenon occurred because the public utilized the river for recreational purposes when the lockdown was lifted. Consequently, local authorities and law enforcement agencies restricted access to islands and beaches by using barricades. The decrease in activity observed at Tilbury can be attributed to the absence of cruise ship departures from the vicinity, given the proximity of the sample location to Tilbury harbor. The port's cargo operations had been temporarily halted during the Covid-19 outbreak. Consequently, the discharge of gray water from cruise ships is reduced, a wastewater stream known for its elevated levels of contaminants. MPs were present in all samples in this study. The findings indicate a correlation between the prevalence of MPs and the occurrence of Covid-19, particularly in relation to samples collected prior to the Covid-19 pandemic and during periods when lockdown measures were not in effect, with a particular emphasis on the second lockdown. The enhanced performance of MPs in this study can be related to suboptimal consumption, inefficiency in disposal, and damage to the face masks employed

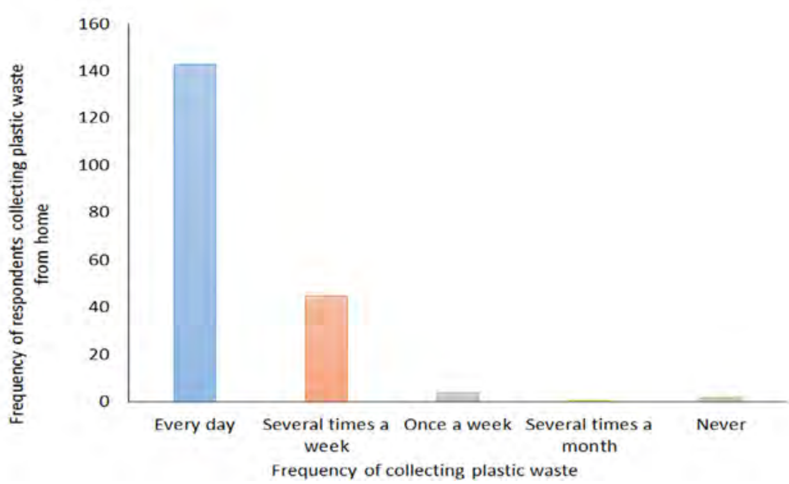

Fig. 2: Frequency of collecting plastic waste from home

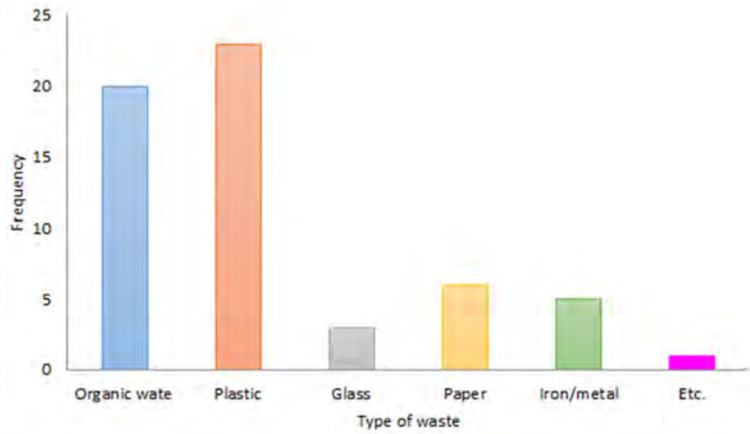

Fig. 3: Handling of plastic waste by the community around Lake Antang

during the epidemic. An investigation was conducted to explore the possibility of rainfall as a contributing factor to the observed high abundance of MPs during the second lockdown. Nevertheless, the abundance of rainfall within the preceding 24-hour period did not exhibit any discernible impact. The impact of the Covid-19 pandemic on plastic pollution globally may not be immediately apparent due to the reduction in production of plastic products, such as masks and gloves. However, the release of MPs into the environment may be exacerbated as a result (Devereux *et al*., 2023). The study results in Fig. 3, showing the waste management process, indicate that an average of 80.7% respondents stated that they disposed their household plastic waste by transporting to a waste collection service, and 18 respondents disposed their household plastic waste by throwing into a hole and covered with soil. Another study stated that 113 (36%) respondents used the household waste disposal method by throwing waste in the open, and 192 (62%) dispose their garbage to trucks (Chikowore, 2021).

As shown in Fig. 2, plastic pollution has significant detrimental impacts on the environment and human health. Fig. 4 shows that the most dominant waste (23) in households is plastic waste, followed by organic waste (20). Thus, the research focuses on household plastic waste. The respondents' knowledge of plastic in Table 2 indicates that as many as 129 respondents confirmed that MP waste could enter the food chain and endanger humans who consume contaminated seafood. In line with this statement, 95% of the respondents stated that they knew that plastic waste harms the marine ecosystems (Charitou *et al*., 2021).

In addition, as shown in Table 2, 146 respondents are aware that plastic waste could pollute the soil, 127 respondents knew that plastic waste could pollute the air, and 100 respondents agree that plastic waste could cause problems for livestock. This study conducted a longitudinal assessment of the availability and distribution of MPs in water bodies within the urban agglomeration of Shanghai Megacity, at the watershed scale. This study examines the impact of MPs conduct on drainage systems, specifically in relation to the occurrence of overflows during wet weather flow (WWF), land utilization, and environmental management techniques. The World Wildlife Fund has the potential to significantly worsen the contamination of MPs in aquatic ecosystems. The comprehensive data analysis indicates that the annual load of MPs discharged through wastewater from their offices is approximately six times higher than the load discharged through effluent from local WWTP within the watershed. The findings of this study provide a valuable contribution to the existing body of research on the regional variability of aquatic MPs and the degree to which they are influenced by land use practices (Chen *et al*., 2020). Table 3 shows how to reduce excess plastic use; 96 respondents agreed that limiting or prohibiting the use of SUP, such as straws, plastic bags, and plastic bottles, can reduce MP pollution; 111 respondents agreed to collect plastic waste from their homes; 99 individuals agreed to sort the trash before throwing because 127 respondents believed that plastic waste would harm human health. This result was confirmed by other research,

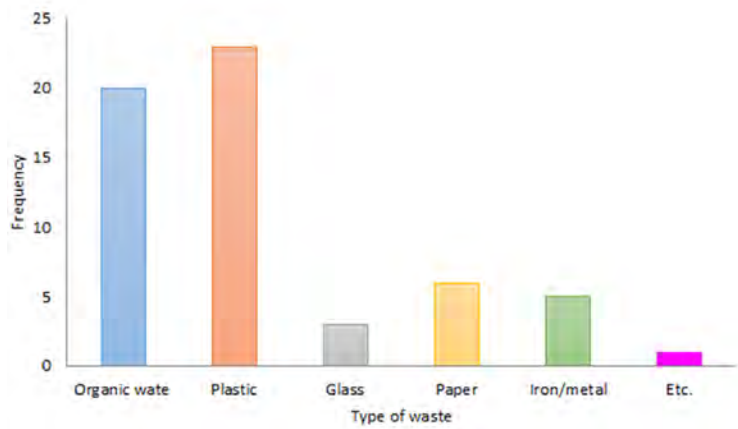

Fig. 4: Type of waste in households

explaining that 22.5% agreed that they would recycle waste (Omoyajowo *et al*., 2021). In addition, 170 respondents participated in sorting waste from their homes prior to disposal, and 324 respondents stated that they had a perception that improper waste management contributed to the emergence of disease (Fadhullah *et al*., 2022). Significant quantities of plastic were discovered at both sites during the course of the study. These items encompass plastic bottles, plastic cups, plastic bags, plastic sachet packaging, food wrap, and fishing nets, among other examples. Establishing a monitoring system for plastic waste leaks is imperative, and stakeholders are expected to perform the necessary repairs. Either 7.20% or 10% of the rubbish is composed of another material given the hypothetical scenario where 29.4% of waste in Bandar Lampung consists of plastic (Schmidt *et al*., 2017). Unmanaged waste has the potential to infiltrate the marine environment, resulting in an approximate influx of 12 tons of plastic waste into the sea on a daily basis from the region of Lampung. In spite of the plastic garbage generated inside these two geographical areas, a substantial volume of waste is observed to traverse national borders. If plastic trash is not recycled and allowed to disintegrate naturally, then fragmentation and the production of MPs occur, posing significant risks to marine ecosystems (Riani and Cordova, 2022). Thus, the use of SUP should be avoided or reduced, and more environmentally friendly alternatives, such as cloth shopping bags or refillable drinking bottles, should be considered. The people can also sort waste and ensure that plastic waste is disposed appropriately to avoid polluting the rivers and the surrounding environment. The community can also participate in river and environmental cleanup programs organized by the government or local environmental organizations. Increasing public awareness about the dangers of plastic pollution and the health risks associated with consuming contaminated fish through campaigns and education can also reduce plastic pollution in rivers. Finally, the public can support government policies to reduce the use of SUP and better manage waste. These actions can reduce plastic pollution in rivers and consequently the health risks associated with consuming contaminated fish (Sabilillah *et al*., 2023). The successful development and implementation of waste management systems by MPs heavily rely on the collaboration of multiple stakeholders. Therefore, the eradication of MPs from the environment is a multidimensional issue that necessitates a comprehensive strategy. Although no universally applicable remedy is available, advancements in catalytic processes and water treatment technologies show intriguing potential for progress. Nevertheless, further investigation and cooperation are required to develop efficient and enduring approaches for eradicating MPs and safeguarding the environment and public health. Improved waste management practices in Indonesia are urgent required to effectively mitigate the leakage of plastic trash, which has the potential to transform into MPs. Considerable emphasis should be placed on the treatment of wastewater in urban areas with high industrial activity and dense population because it plays a significant role in the pollution of water bodies by MPs. The findings of this study underscore the importance of implementing source identification and control strategies to effectively mitigate water contamination caused by MPs. The implementation of efficient waste management techniques, improved wastewater treatment methods, and the dissemination of public awareness campaigns play a crucial role in the preservation of water quality, safeguarding aquatic species, and promoting the well-being of human populations. One way to change people's behavior is to educate them about plastic pollution's health dangers. Thus, strategies should be used to be effective and optimal in providing education. Previous research outlined plans for implementing waste management in the school environment. Teachers empower and engage students to take part in environmental learning and action (Chow *et al*., 2017).

CONCLUSION

Plastic pollution increases with time. Meanwhile, controlling plastic pollution depends on user behavior. Therefore, considering the determinants of plastic user behavior, especially those related to plastic management, is essential. The present study has revealed that, to some extent, the knowledge factor exhibited a statistically significant association with household plastic waste management behavior. This finding was supported by statistical evidence, as indicated by a *p*-value of 0.002 and an OR value of 2.603. By contrast, the relationship between the attitude and action components and household plastic waste management behavior is not statistically significant, as indicated by *p*-values of 0.088 and 0.223, respectively. The regression analysis findings indicate that the knowledge variable (*p*-value = 0.000) exerts a statistically significant impact on plastic waste management behavior. In the present study, the attitude variable has yielded a *p*-value of 0.787, whereas the action variable yielded a *p*-value of 0.295. The regression coefficient value in this study is 0.356 (35.6%). The findings suggest no significant relationship between individuals' views and behavior and their behavior toward waste management, among the three independent variables. Individuals with limited awareness exhibit a 0.118-fold increase in the likelihood of engaging in inadequate domestic plastic waste management practices compared with a strong understanding. A deficiency in public awareness would have adverse implications for waste management practices within the society. This assertion holds true when the community demonstrates an apathetic stance toward trash management, which is reflected in their corresponding behavior. If an individual's behavior is deemed detrimental to waste management, then the efficiency of the waste management process is impeded. Addressing the issue of MP pollution in the environment is a multifaceted challenge that necessitates a comprehensive strategy. This scenario highlights the required fostering collaboration among multiple parties. The implementation of efficient waste management techniques, enhanced wastewater treatment methods, and the dissemination of public awareness campaigns play a pivotal role in the preservation of uncontaminated water sources and the safeguarding of aquatic species and human well-being. Hence, while knowledge, attitudes, and actions may not exhibit direct impact on individuals' behavior regarding waste management, effective plastic waste management should be prioritized to establish prudent waste management practices.

AUTHOR CONTRIBUTIONS

D. Utari prepared the manuscript text, prepared all the maps and figures, and interpretation of the results and manuscript edition. N.I Hawa performed the data analysis and performed the data analysis. G. Fizulmi permorfed the results,. H. Agustina was the corresponding author, supervising the study, obtaining funding, and conceptualization.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
>	More than
<	Less than
–	Until
±	Plus or minus
°C	Degree Celsius
A	Agree
BPA	Bisphenol A
CI	Confidence Interval
Cl	Convidence Level
Covid-19	Corona virus desease 2019
D	Disagree
m^3	Cubic meter
mm	Millimeters
MPs	Microplastics
N	Never
O	Often
OPs	Opportunistic pathogens
OR	Odds ratio
p-value	Probability test value
PA	Polyamide
PET	Polyethylene terephthalate
PS	Polystyrene
PVC	Polyvinyl chloride
R	Correlation coefficient
RE	Rarely
SA	Strongly agree
SD	Strongly disagree
SPSS	Statistical package for the social science
SUP	Single-use plastic
TPA	Tempat pembuangan akhir (landfills)
USD	United States Dollars
UV	Ultra Violet
VO	Very Often
WWF	Wet Weather Flow
WWTP	Wastewater Treatment Plant

REFERENCES

Akdogan, Z.; Guven, B.; Kideys, A.E., (2023). Microplastic distribution in the surface water and sediment of the Ergene River. Environ. Res., 234: 116500 **(11 pages).**

Ali, F.; Azmi, K.N.; Firdaus, M.R., (2021). Existence of microplastics in Indonesia's surface water: A review. Int. J. Intgr. Eng., 13(3): 100–107 **(8 pages).**

Anderson, J.C.; Park, B.J.; Palace, V.P., (2016). Microplastics in aquatic environments: Implications for Canadian ecosystems. Environ. Pollut., 218: 269–280 **(12 pages).**

Arpia, A.A.; Chen, W.H.; Ubando, A.T.; Naqvi, S.R.; Culaba, A.B., (2021). Microplastic degradation as a sustainable concurrent approach for producing biofuel and obliterating hazardous environmental effects: A state-of-the-art review. J. Hazard. Mater., 418: 126381 **(11 pages).**

Buwono, N.R.; Risjani, Y.; Soegianto, A., (2022). Spatio-temporal patterns of occurrence of microplastics in the freshwater fish Gambusia affinis from the Brantas River, Indonesia. Environ. Pollut., 311: 119958 **(32 pages).**

Cerasi, I.R.; Sánchez, F.V.; Gallardo, I.; Górriz, M.Á.; Torrijos, P.; Aliaga, C.; Franco, J., (2021). Household plastic waste habits and attitudes: A pilot study in the city of Valencia. Waste Manage. Res., 39(5): 679-689 **(11 pages).**

Charitou, A.; Aga-Spyridopoulou, R.N.; Mylona, Z.; Beck, R.; McLellan, F.; Addamo, A. M., (2021). Investigating the knowledge and attitude of the Greek public towards marine plastic pollution and the EU single-use plastics directive. Mar. Pollut. Bull., 166: 112182 **(11 pages)**.

Chen, H.; Jia, Q.; Zhao, X.; Li, L.; Nie, Y.; Liu, H.; Ye, J., (2020). The occurrence of microplastics in water bodies in urban agglomerations: Impacts of drainage system overflow in wet weather, catchment land-uses, and environmental management practices. Water Res., 183: 116073 **(1 page).**

Chen, X.; Tao, G.; Wang, Y.; Wei, W.; Lian, X.; Shi, Y.; Chen, S.; Sun, Y., (2022). Interactive impacts of microplastics and chlorine on biological stability and microbial community formation in stagnant water. Water Res., 221 **(23 pages).**

Chen, X.; Lian, X.; Wang, Y.; Chen, S.; Sun, Y.; Tao, G.; Tan, Q.; Feng, J., (2023). Impacts of hydraulic conditions on microplastics biofilm development, shear stresses distribution, and microbial community structures in drinking water distribution pipes. J. Environ. Manage., 325: 116510 **(13 pages).**

Chikowore, N., (2021). Factors influencing household waste management practices in Zimbabwe. J. Mater. Cycles Waste Manage., 23(1): 386-393 **(8 pages).**

Choudhury, M.; Sahoo, S.; Samanta, P.; Tiwari, A.; Tiwari, A.; Chadha, U.; Bhardwaj, P.; Nalluri, A.; Eticha, T.K.; Chakravorty, A., (2022). COVID-19: An accelerator for global plastic consumption and its implications. J. Environ. Public Health, 2022: 1066350 **(17 pages).**

Chow, C.F.; So, W.M.W.; Cheung, T.Y., Yeung, S.K.D., (2017). Plastic waste problem and education for plastic waste management. (eds) Emerging Practices in Scholarship of Learning and Teaching in a Digital Era. Springer, Singapore **(16 pages).**

Cordova, M.R.; Iskandar, M.R.; Muhtadi, A.; Saville, R.; Riani, E., (2022). Spatio-temporal variation and seasonal dynamics of stranded beach anthropogenic debris on Indonesian beach from the results of nationwide monitoring. Mar. Pollut. Bull., 182: 114035 **(3 pages).**

Costa, L.L.; da Silva Oliveira, A.; da Costa, I.D.; Silva, T.N.; Sant'Anna, M.E.A.S.; Tavares, B.; Zalmon, I.R., (2023). Multiple species ingest microplastic but few reflect sediment and water pollution on sandy beaches: A baseline for biomonitoring. Mar. Pollut. Bull., 193: 115235 **(1 page).**

Deng, L.; Cai, L.; Sun, F.; Li, G.; Che, Y., (2020). Public attitudes towards microplastics: Perceptions, behaviors and policy implications. Resour. Conserv. Recycl., 163: 105096 **(11 pages).**

Devereux, R.; Ayati, B.; Westhead, E.K.; Jayaratne, R.; Newport, D., (2023). Impact of the Covid-19 pandemic on microplastic abundance along the River Thames. Mar. Pollut. Bull., 189: 114763 **(13 pages).**

Diez-Pérez, D.B.; Arenas, I.; Maidana, E.; López-Rosales, A.; Andrade, J.M.; Muniategui-Lorenzo, S., (2023). Microplastics in surface water of the Bay of Asunción, Paraguay. Mar. Pollut. Bull., 192: 115075 **(11 pages).**

Enfrin, M.; Dumée, L.F.; Lee, J., (2019). Nano/microplastics in water and wastewater treatment processes–origin, impact and potential solutions. Water Res., 161: 621-638 **(78 pages).**

Fadhullah, W.; Imran, N.I.N.; Ismail, S.N.S.; Jaafar, M.H.; Abdullah, H., (2022). Household solid waste management practices and perceptions among residents in the East Coast of Malaysia. BMC Public Health, 22(1): 1-20 **(20 pages).**

Garello, N.A.; Blettler, M.C.M.; Espínola, L.A.; Rodrigues, S.; Rimondino, G.N.; Wantzen, K.M.; Rabuffetti, A.P.; Girard, P.; Malanca, F.E., (2023). Microplastics distribution in river side bars: The combined effects of water level and wind intensity. Sci. Total Environ., 165406 **(1 page).**

Guzzetti, E.; Sureda, A.; Tejada, S.; Faggio, C., (2018). Microplastic in marine organism: Environmental and toxicological effects. Environ. Toxicol. Pharmacol., 64: 164-171 **(8 pages).**

Jahani, A.; Dehdari, T.; Farzadkia, M.; Mansourian, M., (2019). Iranian experiences in terms of consumption of disposable single-use plastics: Introduction to theoretical variables for developing environmental health promotion efforts. Environ. Toxicol. Pharmacol., 65: 18–22 **(5 pages).**

Karbassi, A.R.; Pazoki, M., (2015). Environmental Qualitative assessment of rivers sediments . Global J. Environ. Sci. Manage., 1 (2): 109-116 **(8 pages).**

Katyal, D.; Kong, E.; Villanueva, J., (2020). Microplastics in the environment: impact on human health and future mitigation strategies. Environ. Health Rev., 63(1): 27-31 **(5 pages).**

Koumi, A.R.; Ouattara-Soro, F.S.; Quéré, Y.; Louault, Y.; N'cho, A.J.Y.; Coulibaly, S.; Cecchi, P., (2021). Les déchets plastiques dans l'océan au cœur de l'Aquathon d'Abidjan, Côte d'Ivoire, Plastic waste in the ocean at the core of the Aquathon meeting in Abidjan, Ivory Coast. Nat. Sci. Soc., 29(4): 458-468. **(11 pages).**

Kumar, R.; Verma, A.; Shome, A.; Sinha, R.; Sinha, S.; Jha, P.K.; Prasad, P.V.P., (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustainability. 13(17): 9963 **(40 pages).**

Mihai, F.C.; Gündoğdu, S.; Markley, L.A.; Olivelli, A.; Khan, F.R.; Gwinnett, C.; Molinos-Senante, M., (2021). Plastic pollution, waste management issues, and circular economy opportunities in rural communities. Sustainability, 14(1): 20 **(48 pages).**

Oguge, N.; Oremo, F.; Adhiambo, S., (2021). Investigating the knowledge and attitudes towards plastic pollution among the youth in Nairobi, Kenya. Social Sci., 10(11): 408 **(13 pages).**

Okunola, A.A.; Kehinde, I.O.; Oluwaseun, A.; Olufiropo E.A., (2019). Public and environmental health effects of plastic wastes disposal: A review. J. Toxicol. Risk Assess., 5(1): 021 **(13 pages).**

Omoyajowo, K.; Raimi, M.; Waleola, T.; Odipe, O.; Ogunyebi, A., (2021). Public awareness, knowledge, attitude and perception on microplastics pollution around lagos lagoon. Ecol. Saf. Balanced Use of Resour., 2(24): 35-46 **(12 pages).**

Rahmawati, A., (2023). Mikroplastik: wujudnya tak nampak dan dampaknya tak terduga. Kementrian Kesehatan Republik Indonesia.

Raja, K.; Bhakta, H.; Prakash, V.; Samal, B.; Bhattacharya, J., (2020). Challenges and strategies for effective plastic waste management during and post Covid-19 pandemic. Sci. Total Environ., 750: 141514 **(10 pages).**

Riani, E.; Cordova, M.R., (2022). Microplastic ingestion by the sandfish Holothuria scabra in Lampung and Sumbawa, Indonesia. Mar. Pollut. Bull., 175: 113134 **(8 page).**

Saat, N.Z.M.; Hanawi, S.A.; Subhi, N.; Zulfakar, S.S.; Wahab, M.I.A., (2018). Practice and attitude on household waste management in Tumpat and Kuala Krai, Kelantan. Res. J. Soc. Sci., 11(1): 14-17 **(4 pages).**

Sabilillah, A.M.; Palupi, F.R.; Adji, B.K.; Nugroho, A.P., (2023). Health risk assessment and microplastic pollution in streams through accumulation and interaction by heavy metals. Global J. Environ. Sci. Manage., 9(4): 719-740 **(22 pages).**

Samimi, M.; Moghadam, H., (2024). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustain. Energy Rev., 190: 113969 **(10 pages).**

Sarkodie, S.A.; Owusu, P.A., (2021). Impact of COVID-19 pandemic on waste management. Environ. Dev. Sustainability, 23: 7951-7960 **(10 pages).**

Schmidt, C.; Krauth, T.; Wagner, S., (2017). Export of plastic debris by rivers into the sea. Environ. Sci. Technol., 51(21): 12246-12253 **(8 pages).**

Sloop, G.D.; De Mast, Q.; Pop, G.; Weidman, J.J.; Cyr, J.A.S., (2020). The role of blood viscosity in infectious diseases. Cureus, 12(2): e7090 **(8 pages).**

Stead, J.L.; Bond, T., (2023). The impact of riverine particles on the vertical velocities of large microplastics. Sci. Total Environ., 896: 165339 **(9 pages).**

Thanh, N.P.; Matsui, Y.; Fujiwara, T., (2011). Assessment of plastic waste generation and its potential recycling of household solid waste in Can Tho City, Vietnam. Environ. Monit. Assess., 175: 23-35 **(13 pages).**

Van Rensburg, M.L.; Nkomo, S.L.; Dube, T., (2020). The 'plastic waste era': Social perceptions towards single-use plastic consumption and impacts on the marine environment in Durban, South Africa. Appl. Geogr., 114(May 2019): 102132 **(9 pages).**

Velmurugan, P.M.; Vijayaprabhakaran, K.; Devika, P.T., (2023). Baseline study on identification, characterization, distribution and abundance of microplastics in surface water from Ennore to Kovalam along the east coast of India. Phys. Chem. Earth, Parts A/B/C, 13: 103391 **(6 pages).**

Wu, J.; Ye, Q.; Sun, L.; Liu, J.; Huang, M.; Wang, T.; Wu, P.; Zhu, N., (2023). Impact of persistent rain on microplastics distribution and plastisphere community: A field study in the Pearl River, China. Sci. Total Environ., 879: 163066 **(13 pages).**

Yang, S.; Zhou, M.; Chen, X.; Hu, L.; Xu, Y.; Fu, W.; Li, C., (2022). A comparative review of microplastics in lake systems from different countries and regions. Chemosphere, 286: 131806 **(13 pages).**

Yee, M.S.L.; Hii, L.W.; Looi, C.K.; Lim, W.M.; Wong, S.F.; Kok, Y.Y.; Tan, B.K.; Wong, C.Y.; Leong, C.O., (2021). Impact of microplastics and nanoplastics on human health. Nanomaterials, 11(2): 496 **(22 pages).**

Yuan, D.; Corvianawatie, C.; Cordova, M.R.; Surinati, D.; Li, Y.; Wang, Z.; Li, X.; Li, R.; Wang, J.; He, L.; Yuan, A.N.; Dirhamsyah, D.; Arifin, Z.; Sun, X.; Isobe, A., (2023). Microplastics in the tropical Northwestern Pacific Ocean and the Indonesian seas. J. Sea Res., 102406 **(9 pages).**

Zhang, S.; Hu, D.; Lin, T.; Li, W.; Zhao, R.; Yang, H.; Jiang, L., (2021). Determinants affecting residents' waste classification intention and behavior: A study based on TPB and ABC methodology. J. Environ. Manage., 290: 112591 **(7 pages).**

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ORIGINAL RESEARCH PAPER

Optimization of industrial symbiosis in coffee-based eco-industrial park design

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ABSTRACT

BACKGROUND AND OBJECTIVES: The coffee agroindustry in Indonesia plays a significant economic role as the third largest coffee producer worldwide. Despite the high economic contribution, the coffee agroindustry also raises environmental issues along its supply chain. Coffee solid waste constitutes biomass containing useful compounds promising as raw materials for added-value products through the implementation of industrial symbiosis. Eco-industrial parks create value through industrial symbiosis, emphasizing the principle of a closed-loop production system, simultaneously decreasing the use of raw materials and waste. This study aimed to analyze and develop a coffee-based eco-industrial park design via a systems engineering approach and optimization of industrial symbiosis in closed-loop coffee production.

METHODS: This study employed a case study in the Ketakasi coffee-producing center in Jember, Indonesia. Data collection was conducted through field observation and a series of in-depth interviews. The development of eco-industrial park design followed a systems engineering methodology, as demonstrated through the utilization of Business Process Model and Notation. Subsequently, the optimization of industrial symbiosis within eco-industrial parks was realized using a mixed-integer linear programming mathematical model.

FINDINGS: The eco-industrial park design presents the actors, internal business processes, material and data exchanges, various actors' interdependence and critical roles in material exchanges, and value creation processes using valorization within the eco-industrial park. The role of the Ketakasi cooperative as a facilitator of material exchange and manager of the eco-industrial park is pivotal. The utilization of data integration enhances the transparency and efficiency of information exchange among eco-industrial park participants, promoting predictability and reliability in material exchange. The application of the mixed-integer linear programming optimization model has provided a structured approach to maximizing the value creation within the eco-industrial park through the valorization of 72.3 percent of coffee pulp and 68.5 percent of spent coffee grounds into cellulase enzymes and ultraviolet shields.

CONCLUSION: This paper presents a structured framework for efficiently managing material exchange processes within an eco-industrial park, contributing to environmental sustainability and economic value creation. This study contributes to the knowledge gap in the literature by developing an inclusive eco-industrial park design that facilitates the optimization of the value creation process through valorization technology. This study also adds to sustainable agriculture management literature through a coffee-based eco-industrial park design.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
83	6	6

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INTRODUCTION

The extensive industrial growth driven by capital investment leads to significant natural resource consumption and environmental issues (Shen and Peng, 2020; Samimi *et al.,* 2023). Circular economy (CE) is an economic model striving to separate economic expansion from the exhaustion of resources and environmental decline (Farooque *et al.*, 2022). This model aims to shift the traditional linear "take–make–dispose" model with a restorative system emphasizing recycling waste materials and effectively recovering the waste value (Yu *et al.,* 2021). CE promotes maximum recycling regarding the increasing resource availability constraints to improve resource use efficiency and effectiveness, leading to resource conservation (Ghisellini *et al.*, 2018). A linear economy extracts resources, transforms them into products, uses them, and disposes them as waste. By contrast, CE promotes resource efficiency, sustainability, and the continuous use of materials in closed-loop systems (Bai *et al*., 2019). CE offers novel perspectives to industrial enterprises, aiming to enhance efficiency by reducing the consumption of materials and natural resources and promoting the reuse of products, materials, and by-products (Kirchherr *et al.*, 2017). One promising method to achieve CE is by establishing industrial symbiosis (IS), a concept inspired by natural ecosystems where different organisms work together for mutual advantage (Tumilar *et al.*, 2020). IS is defined as a concept in which traditionally separate entities collaborate for mutual competitive benefits, encompassing the physical sharing of materials, energy, water, and by-products (Neves *et al.*, 2020). The key principles of IS include efficient use of resources, waste reduction, and collaborative advantage, all contributing to economic, environmental, and social benefits (Stucki *et al.*, 2019). Adopting IS in industrial systems offers economic and environmental benefits, including enhanced profitability and competitiveness by reducing raw material and disposal costs, innovation and new revenue streams, collaborative networks, environmental regulation compliance, and decreased emissions and environmental pollution (Tolstykh *et al.*, 2023). IS encourages companies to shift from linear production to a circular model, prompting the re-evaluation and redesign of supply chains and considering new stakeholders, waste's impact on product development, economic investments, and technological resources (Demartini *et al.,* 2022). IS focuses on the concept of deriving values through waste sharing; in fact, what is regarded as waste by one company can serve as a resource for another (Lawal *et al.,* 2021). Substituting inputs with waste materials enables companies to boost their production efficiency, leading to cost savings by reducing waste disposal and input procurement expenses (Fraccascia and Yazan, 2018). The potential for reusing waste materials emerges through integrating industrial clusters to establish IS and effectively create closed-loop cycles of materials (Ormazabal *et al.*, 2018). An eco-industrial park (EIP) is described as an embodiment of the IS concept at the meso/industrial level (ElMassah, 2018), where distinct industrial entities come together and achieve a measure of IS (Belaud *et al.*, 2019). The concept of EIP promotes implementing an analogical model based on natural ecosystems to enhance resource utilization efficiency on a park scale, ultimately aiming for a sustainable industrial system regarding the social, economic, and environmental aspects of sustainability (Valenzuela-Venegas *et al*., 2016). EIP increases industrial system sustainability through the improvement of environmental performance, including great economic growth, diminished resource consumption, and decreased pollution and emission (Liu *et al.,* 2015). EIP has fostered beneficial connections between colocated firms, encouraging them to share natural and economic resources and enhancing sustainability and economic gains (Kastner *et al.*, 2015). EIP creates value through IS, emphasizing the principle of a closed-loop system within EIP and simultaneously decreasing the use of raw materials and waste (Winans *et al.*, 2017; Fan *et al.*, 2017). As a representative of closed-loop initiatives of IS conducted on a cluster scale, EIP promotes a cluster of proximate firms that collaboratively share specific resource and energy flows, thereby augmenting their combined energy and resource efficiency (Chen *et al.*, 2023). In practice, operations within an EIP experience daily fluctuations, leading to a continuous encounter with uncertainty (Liberona *et al.*, 2023). EIP performance is evaluated from how the closed-loop design functions effectively through IS optimization within EIP, including waste and by-product exchange optimization (Yu *et al.*, 2023). An efficient EIP design aims for maximum cyclicity, minimizing waste outflow and external resource procurement (Genc *et al.,* 2020). IS optimization is crucial to attain maximum cyclicity in the design of EIPs, in consideration of the involvement of diverse stakeholders and their respective interests. A systematic literature review was conducted to scrutinize the state of the art in IS optimization in EIP literature by using the Scopus database. Publication searches were carried out through the search engine in the Scopus database using the keywords "eco-industrial park" and "optimization," and 207 papers published from 2003 to 2023 were collected.

Based on the subject area, previous studies on IS optimization in EIP mostly focused on environmental science, engineering, and energy fields (Fig. 1). On the contrary, EIP optimization in the agriculture field, including agroindustry, is the least addressed with 1.3 percent (%) of total publication number. The 207 papers were reviewed through an iteration process, including the summarize, synthesize, compare, and criticize stages, resulting in 7 main papers that are state of the art in this research (Table 1).

The general method utilized in the optimization of IS in EIP identified from the literature review is a quantitative approach using mathematical models, namely, the mixed-integer linear programming (MILP) and the mixed-integer nonlinear programming (MINLP). Table 1 summarizes that optimization of IS within EIP was carried out using the MILP method to obtain the optimum solution for operating cost (Yu *et al.*, 2023), total cost of system (Ventura *et al.*, 2023), operational cost saving (Jing *et al.*, 2021), water consumption (Aussel *et al.*, 2023), energy exchange (Mousque *et al.*, 2020), and wastewater treatment cost (Hu *et al.*, 2020). The MINLP method was employed to obtain the optimum solution for energy exchange (Misrol *et al.*, 2022). In developing the MILP and MINLP optimization models, these studies focused on the objective function of EIP operational cost efficiency, as well as optimizing energy distribution and water consumption within EIP. Limitations in these studies were identified, resulting in knowledge gaps, including the lack of perspective

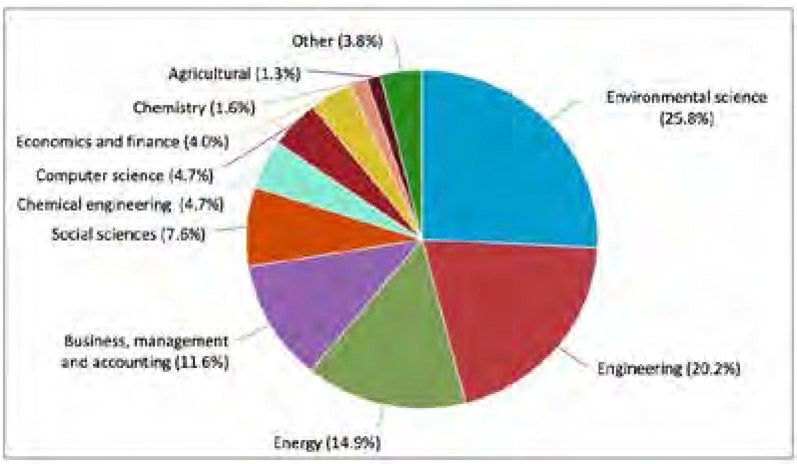

Fig. 1: Literature on IS optimization within EIP from 2003 to 2023 based on the subject area in the Scopus database

Table 1: State-of-the-art previous studies on IS optimization in EIP based on Scopus database

Optimization method	Objective function	Sources
Mixed-integer linear programming	Optimization of operating cost	Yu *et al.*, 2023
Mixed-integer linear programming	Optimization of the total cost of system	Ventura *et al.*, 2023
Mixed-integer linear programming	Optimization of water consumption	Aussel *et al.*, 2023
Mixed-integer nonlinear programming	Optimization of energy exchange	Misrol *et al.*, 2022
Mixed-integer linear programming	Optimization of operational cost saving	Jing *et al.*, 2021
Mixed-integer linear programming	Optimization of energy exchange	Mousque *et al.*, 2020
Mixed-integer linear programming	Optimization of wastewater treatment cost	Hu *et al.*, 2020

objective function on optimization for value creation in terms of waste valorization into added-value products and the lack of addressing the dynamics and interdependence of actors' interests within EIP, which influence their business process. EIP, as an industrial system, is composed of business entities primarily focused on conducting business operations, carrying out the value creation process, and creating economic profits. The process of value creation is an important function facilitated by EIP in parallel with the aim of minimizing environmental impacts. The implication is that optimizing the value creation process in EIP through technology valorization is urgent and important to fill the literature gap. The challenge of the value creation optimization in EIP is to build material exchanges that are economically mutually beneficial for all EIP participants (Afshari *et al.*, 2018). This study addresses this knowledge gap by developing an inclusive EIP design that facilitates the optimization of the value creation process through valorization technology. Optimization of the value creation process is carried out with the perspective of maximizing the amount of valorized waste converted into value-added products, which also has an impact on minimizing untreated waste disposed into the environment. The outcome of the EIP design in this study will contribute to maximizing added value and minimizing environmental costs. Previous studies predominantly concentrated on the context of developed countries, whereas EIP optimization within the context of developing countries was not well addressed (Perrucci *et al.*, 2022). Through a case study within Indonesia's coffee agroindustry, this study contributes to addressing the gap in the literature concerning EIP development in developing countries. Indonesia plays a significant economic role as the third largest coffee producer worldwide after Brazil and Vietnam. Coffee plantations were the third largest after oil palm and rubber plantations in Indonesia in 2021, contributing 16.15% to its gross domestic product and providing a livelihood for 7.8 million Indonesian farmers (BPS Indonesia, 2022). Despite the high economic contribution, the coffee agroindustry also raises environmental issues along its supply chain, including deforestation, water pollution, and greenhouse gas (GHG) emissions (Laili *et al.*, 2022). Coffee processing generates wastewater that contains mucus and remnants from fermentation, which is notable for its corrosive nature and high acidity (Sahana *et al.*, 2018). Similarly, solid waste such as pulp, husk, silver skin, and residues generated from fertilizers and herbicides (Chala *et al.*, 2018) contribute to soil pollution and eutrophication (Woldesenbet *et al.*, 2016). Such coffee waste leads to the emission of GHG air pollution due to energy use in production and transportation processes (Ribeiro *et al.*, 2018), as well as carbon emissions and accumulated impacts on human health (Giraldi-Diaz *et al.*, 2018). Coffee solid waste constitutes biomass containing useful compounds, including carbohydrates, cellulose, hemicellulose, lignin, lipids, proteins, ash, caffeine, tannins, chlorogenic acids, and pectins (Nguyen *et al.*, 2019; Santos *et al.*, 2021). Such waste is potentially used as raw materials for valuable products, including biosugar, biofuel, fertilizers, enzymes, dietary fiber, and bioactive compounds (Durán-Aranguren *et al.*, 2021). Coffee solid waste comprises a substantial portion of the coffee cherry biomass during coffee processing, reaching 50% pulp and 20% husk (Arya *et al.*, 2022). Abundant coffee solid waste, including agricultural by-products, is a type of waste stream exchange common to most networks in EIP (Domenech *et al.*, 2019). The coffee agroindustry in Indonesia has the potential to be developed into an EIP through the implementation of IS. When applied in the coffee agroindustry, IS encourages coffee industries to collaborate and use one another's by-products, leading to reductions in the use of raw materials, production costs, and environmental pollution. Coffee-based EIP is designed to facilitate IS in the form of material exchange for coffee solid waste, then continue with the process of valorizing this coffee solid waste into value-added products by using certain technology. This process describes the implementation of IS in the coffee agroindustry, where coffee by-products are exchanged and become raw materials for other industries. This study aimed to analyze and develop a coffee-based EIP design through a systems engineering approach and optimization of IS in closed-loop coffee production. This study was conducted in the Ketakasi coffee-producing center, Jember Regency, in East Java Province, Indonesia from 2022 to 2023.

MATERIALS AND METHODS

East Java Province ranks as the fifth-largest coffee producer in Indonesia, and within this province, Jember Regency is known as a prominent coffee-

Fig. 2: Geographical location of the Ketakasi coffee-producing center in Jember Regency, East Java Province, Indonesia (red square)

producing area. This research was conducted in the Ketakasi coffee-producing center located in Sidomulyo Village, Silo District, Jember, East Java Province, Indonesia (Fig. 2). The development of EIP design followed a systems engineering methodology, as demonstrated through the utilization of Business Process Model and Notation (BPMN). Subsequently, this study optimized IS within the material exchange, delineated earlier in a BPMN-based EIP framework.

Case study location and data collection

The climate in Jember Regency, including the Ketakasi coffee-producing center, is tropical. Temperature figures range between 23 degrees Celsius (°C) and 31 °C, with the dry season occurring from May to August and the rainy season occurring from September to January. Considerable rainfall occurs, ranging from 1,969 millimeters (mm) to 3,394 mm. Geographically, the case study is located at 7°59′6″–8°33′56″ south latitudes and 113°16′28″–114°03′42″ east longitudes. The territory covers an area of 3,293.34 kilometers square (km^2), with a topographical characteristic of fertile canyon plains in the central and southern parts, surrounded by mountains along the western and eastern boundaries. The elevation of this regency ranges from 0 meters above sea level (masl) to 3,300 masl, with the majority of the area (37.75%) at an altitude of 100–500 masl, 17.95% at 0–25 masl, 20.70% at 25–100 masl, 15.80% at 500–1,000 masl, and 7.80% at over 1,000 masl. The southwest region has plains at 0–25 masl, while the northeastern region bordering Bondowoso and the southeastern bordering Banyuwangi have altitudes above 1,000 masl. Ketakasi is a robusta coffee-producing center with a cooperative business entity that was founded in 2007. The Ketakasi Cooperative comprises 620 farmers cultivating robusta coffee across a total area of 1,327 ha. In 2022, Ketakasi produced 2,300 tons of robusta coffee, with 95% of the output being green beans and 5% being processed coffee products. The market shares of Ketakasi's robusta coffee production, constituting 95%, is allocated for export as green beans, with the remaining 5% designated for domestic consumption. Processed coffee products for the domestic market are roasted coffee beans and ground coffee under the Ketakasi brand.

Data collection was carried out from February 2022 to March 2023 to obtain primary and secondary data. Primary data were collected through field observation techniques and a series of in-depth interviews. Comprehensive field observations encompassing the entire Ketakasi coffee agroindustry supply chain and its vicinity were conducted. This process involved the examination of coffee farmers and their plantations, the production processes within Ketakasi, the coffee processing industry/small- and medium-sized enterprises (SMEs), and the management of coffee waste and existing waste processing methods. In

Table 2: Detail of informants and interviewees in data collection

Actors	Number of interviewees
Coffee farmer	32 informants
Coffee farmer group	7 groups
Coffee industry/SMEs	18 firms
Management of the Ketakasi cooperative	3 informants
Coffee waste processor	2 SMEs
Coffee researcher from Jember University	5 informants
Researchers from the Coffee and Cocoa Research Center	3 informants
Department of Food Crops, Horticulture, and Plantation	2 informants

parallel, in-depth interviews were conducted to obtain primary data, with details of informants and the number of interviewees, as shown in Table 2. This study utilized semistructured questionnaires for primary data collection through a series of in-depth interviews. Semistructured questionnaires are a flexible data collection method commonly used in case studies because this method balances the need for specific information with the flexibility to probe further (Ruslin *et al.*, 2022). These questionnaires include a mix of predetermined questions and opportunities for open-ended responses. Semi-structured questionnaires explore certain topics in depth while keeping the structure of interviews. In this study, in-depth interviews were conducted following semistructured questionnaires in the form of a set of open-ended questions structured on the basis of seven main topics. During in-depth interviews, questions were developed to explore additional details but remained focused on the context of the seven main topics. The depth of answers of each informant differed. The seven main topics were as follows: 1) developments in the coffee supply chain and its stakeholders over the past 5 years; 2) business processes, production procedures, product transformation, and value addition of each actor in coffee supply chain; 3) sustainability pillars, including technological, social, and economic dimensions of the coffee agroindustry; 4) potential and existing coffee waste valorization process; 5) research and development activities related to coffee processing and waste valorization; 6) coffee waste generation and management; and 7) flow of materials in coffee agroindustry. The same open-ended questions were posed to multiple informants to ensure a diversity of perspectives and enhance data validation and triangulation.

Subsequently, secondary data were collected through a literature review to obtain information on EIP development, including potential by-product/waste generation and exchange, socioeconomic conditions, natural resources, technology characteristics, coffee environmental impact report, and relevant regulation and policy. These data were collected from reports of coffee farmers, coffee industry/SMEs, Ketakasi cooperative, Jember Regency government, statistical data related to the coffee agroindustry, previous studies, and other relevant documentation.

Systems engineering approach—BPMN

Systems engineering is a multidisciplined approach that integrates analytical, mathematical, and scientific principles to formulate, select, develop, and refine optimal solutions from viable candidates, considering acceptable risk, user operational needs, cost minimization, and stakeholder interests (Wasson, 2015). Regarding complexity, EIP is a highly complex system involving the interaction and transfer of material, energy, and water between firms within the system (Devanand *et al.*, 2020). Designing EIPs demands a comprehensive, multidisciplinary, and thorough approach, and systems engineering offers the framework, techniques, and resources needed to efficiently strategize, create, and oversee EIPs, ensuring their alignment with environmental, economic, and social sustainability goals. In this study, BPMN, a systems engineering tool, is employed to create a coffee-based EIP in Ketakasi. BPMN provides a standardized way to represent business processes, which is beneficial in the context of EIP for process visualization, process optimization, and interoperability interactions and workflows between different entities (Martins *et al.*, 2019; Schaffer *et al.*, 2021) and is essential in EIPs where multiple firms collaborate and share resources. This study uses BPMN to design EIP using the unified modeling language and SAP PowerDesigner 16.6 software.

Optimization IS—MILP mathematical model

MILP modeling is a widely recognized and established methodology employed across diverse domains to address optimization challenges, encompassing its application within the realm of IS optimization in the context of EIP. Previous studies showed that the MILP model has been implemented for water exchange in EIP in consideration of water quality (Tiu and Cruz, 2017), optimization of energy symbiotic network exchange within EIP (Afshari *et al.*, 2020; Neri *et al.*, 2023), and optimization of utility exchange between different plants within EIP (Galvan-Cara *et al.*, 2022). Most EIP optimization studies focused on optimizing one of three main categories: water, energy/heat, and materials (Boix *et al.*, 2015). Within these three categories, water exchange optimization has garnered the most extensive attention in the existing literature, whereas material exchange optimization remains less addressed (Tiu and Cruz, 2017), which is the focus of this study. Wolsey (2020) defined a general mathematical model in MILP (Table 3), typically consisting of the following components: objective function, decision variables, constraints, bounds on variables, and integrality constraint.

RESULTS AND DISCUSSION

This study undertakes the analysis and formulation of a coffee-based EIP design in Ketakasi using BPMN within a systems engineering framework. Subsequently, this study optimizes the IS, specifically focusing on enhancing the material exchange aspect within the established EIP design.

BPMN of coffee-based EIP design in Ketakasi

Ketakasi is a robusta coffee-producing center with a cooperative business entity that was founded in 2007. The Ketakasi cooperative comprises 620 farmers cultivating robusta coffee across a total area of 1,327 ha. In 2022, Ketakasi produced 2,300 tons of robusta coffee, with 95% of the output being green beans and 5% being processed coffee products. In this study, the wet processing method is used to produce coffee beans, involving a fermentation process that produced high-quality coffee beans. For every 1 kilogram (kg) of coffee cherry being processed, approximately 25%–35% is converted into coffee beans or derivative products, while 65%–75% constitutes solid waste, namely, coffee pulp and spent coffee grounds (SCG), (Fig. 3). The coffee industry also processes coffee into roasted coffee beans, ground coffee, and coffee extract and generates solid waste in the form of SCG.

This study focuses on coffee solid waste, namely, coffee pulp and SCG. The coffee pulp and SCG produced from coffee agroindustry activities in Ketakasi and its surroundings in the period 2018–2022 are shown in Fig. 4. The solid waste generated has fluctuated over the last 5 years with an increasing trend. This trend is in line with that of the national coffee production, which also tends to increase every year. During the period 2018–2022, an average of 4,760 tons of coffee pulp and 4,679 tons of SCG was generated per year. Of this amount of solid waste, only 15% was processed into animal feed and fertilizer, while 85% was untreated and disposed of in the environment. Continuously disposing of untreated coffee solid waste into the environment potentially raises environmental issues, including soil pollution and eutrophication (Capanoglu *et al.*, 2022).

Apart from abundance in quantities, the characteristics of coffee pulp and SCG as types of agricultural biomass are also indicated by the

Table 3: General mathematical model in MILP (Wolsey, 2020)

Components	Mathematical model
Objective function	Max Z = $c_1 x_1 + c_2 x_2 + ... + c_n x_n$
Subject to constraints	$a_{11} x_1 + a_{12} x_2 + ... + a_{1n} x_n < b_1$
	$a_{21} x_1 + a_{22} x_2 + ... + a_{2n} x_n > b_2$
	...
	$a_{m1} x_1 + a_{m2} x_2 + ... + a_{mn} x_n > b_m$
Non-negative restrictions	$x_1, x_2, x_3, ... x_n >= 0$
Decision variables	$x_1, x_2, x_3, ... x_n$

Fig. 3: Coffee pulp and SCG

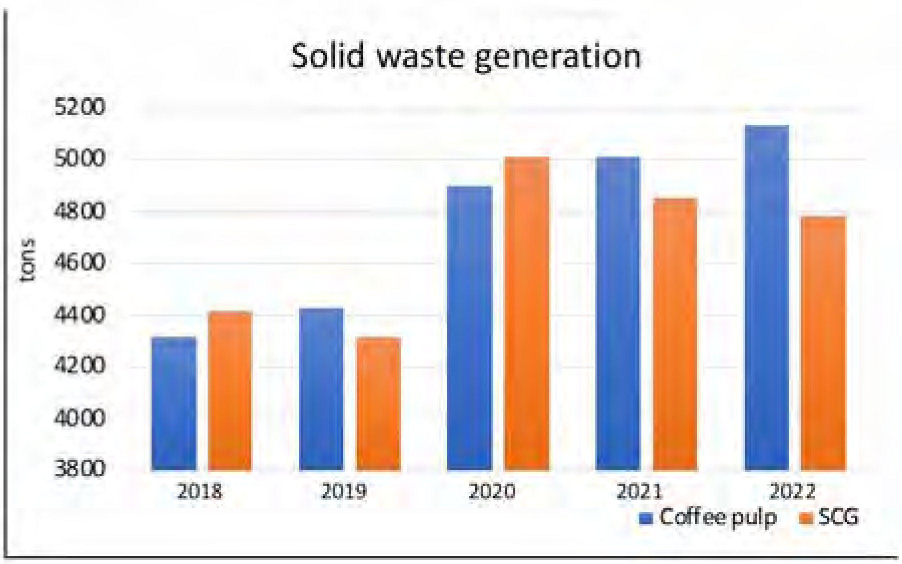

Fig. 4: Solid waste generated in the period 2018–2022

chemical compound content, such as carbohydrates, cellulose, hemicellulose, lignin, lipids, proteins, caffeine, and tannins, as detailed in Table 4. This chemical content makes coffee pulp and SCG have the potential to become raw materials for various value-added products through valorization. The chemical compounds contained in coffee pulp and SCG are determined by coffee processing methods and coffee variety (Blinova and Sirotiak, 2019).

The largest coffee-producing countries in the world are developing countries, namely, Brazil, Vietnam, Indonesia, Colombia, and Ethiopia, which export coffee in the form of green beans. Hence, primary coffee processing takes place in developing countries

Table 4: Chemical compounds in coffee waste (% dry matter) (Nguyen *et al*., 2019; Santos *et al*., 2021)

Chemical compounds	Coffee pulp	Coffee husk	SCG
Carbohydrates	44.0–55.0	57.8	60.3–82.0
Cellulose	9.18–63.0	39.0–61.0	8.6–47.3
Hemicellulose	2.0–66.0	4.0–10.0	32.0–43.0
Xylose	-	-	0.3–1.1
Arabinose	-	-	1.7–3.6
Mannose	-	-	19.1–21.6
Galactose	-	-	8.2–16.4
Rhamnose	-	-	0.1
Lignin	12.2–22	9.0	23.9–33.6
Lipids	0.3–2.5	0.5–6.0	6.0–38.6
Proteins	4.4–12.0	3.0–13.0	11.5–18.0
Ash	5.4–15.4	6.0	1.1–2.2
Caffeine	0.8–5.7	0.5–2.0	0.02–0.4
Tannins	1.8–8.6	4.5–9.3	0.02
Chlorogenic Acids	1.0–10.7	2.0–12.6	1.8–11.5
Pectins	4.4–12.4	0.5–3.0	0.01

to produce green beans. This process generates the greatest proportion of coffee waste in the form of coffee wastewater and coffee solid waste. When coffee cherries are processed to produce green beans, 65%–75% of the mass of the coffee cherries will become solid waste in the form of coffee pulp, coffee husk, and SCG. Meanwhile, developed countries, namely, the US, Canada, and European countries, are the world's largest coffee consumers. The coffee production process carried out in developed countries is secondary and tertiary production to produce roasted coffee beans, ground coffee, and extracted coffee. This process has implications for the waste produced, which is generally in the form of SCG. The generation of coffee waste is also influenced by the management and mastery of coffee waste processing technology. The presence of sophisticated waste management systems in developed countries typically allows for the systematic reduction, reuse, and recycling of coffee waste, aligning with the rigorous environmental regulations that govern waste management practices. As such, developed countries may not only generate more coffee waste but are also more likely to have established mechanisms for its efficient processing and diversion from landfills. Conversely, the coffee processing methods in developing countries often hew to traditional approaches, which may be less efficient and yield a greater quantum of waste relative to the volume of coffee cherries processed. The infrastructure for waste management in developing countries is frequently less developed, potentially leading to less efficient handling of coffee waste and greater environmental impact. Utilizing SAP® Power-Designer 16 software as the design tool, this study designs a comprehensive BPMN representation for a coffee-based EIP in Ketakasi. Fig. 5 shows the BPMN diagram, which elucidates the pertinent actors within EIP, the internal business processes of each actor, the material flows and exchanges between participants within EIP, the flows of data and information, the automated decision points at gateways, and the integration of data streams across EIP. This figure features two distinct types of flows: material flow, represented by solid lines, and data flow, depicted using dotted lines. The EIP design comprises five distinct business entities, each of which is delineated within its respective swimlane. These actors are farmers, coffee firms or SMEs, the Ketakasi cooperative, cellulase enzyme producers, and ultraviolet (UV) shield producers. The business and production activities carried out within each swimlane represent routine internal business processes specific to each actor.

Within the EIP, 620 farmers collectively have 1,327 ha of land allocated for the cultivation of robusta coffee. The internal business process of the farmers commences with the coffee harvesting process, followed by coffee processing using the wet processing method, and the production of coffee hard skin (hs), which is subsequently supplied to

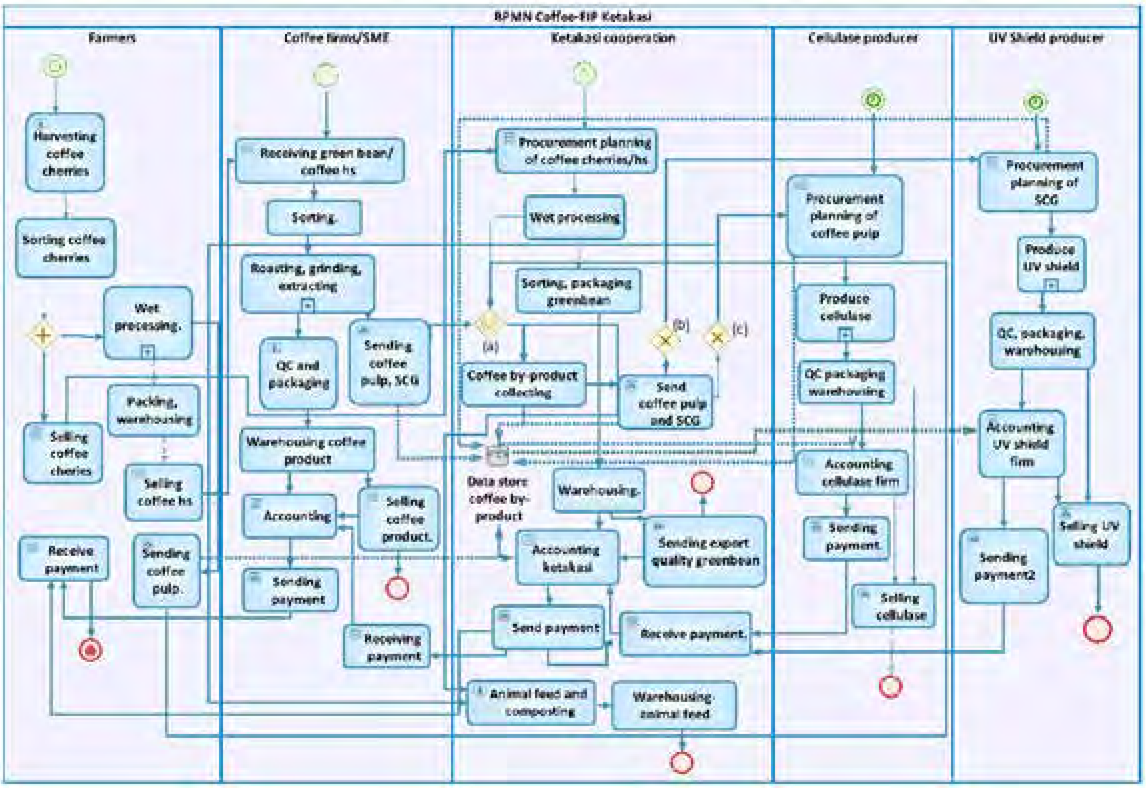

Fig. 5: BPMN of coffee-based EIP design in Ketakasi (a) gateway automation screening coffee by-product, (b) gateway SCG, (c) gateway coffee pulp

coffee firms/SMEs and the Ketakasi cooperative. Notably, because of constraints in wet processing capacity, farmers are compelled to sell a portion of their harvest in the form of coffee cherries. Within the EIP, 22 coffee firms/SMEs engage in internal business processes encompassing production processes. These processes entail using raw materials, including coffee cherries or coffee hs, to produce roasted coffee beans, coffee grounds, and coffee extracts. The Ketakasi cooperative holds a pivotal role as the EIP's manager, facilitating interactions between all EIP actors through material exchanges. The internal business process at the Ketakasi cooperative encompasses various activities, including the production of green beans for export markets, the management of coffee by-product exchanges, and the production of animal feed and fertilizers. Two actors within the EIP, namely, the cellulase producer and the UV shield producer, are actively engaged in valorizing coffee waste. The cellulase producer's internal business process involves the generation of cellulase enzymes derived from coffee pulp via a solid-state fermentation (SSF) process employing *Acinetobacter sp*. The valorization of coffee pulp into cellulase enzyme within EIP exemplifies the practice of IS, in which the by-product is treated as an input material for other production cycles. Previous studies showed that various agroindustry by-products have been valorized using different microbial strains through SSF (Sivakumar *et al.*, 2022). The critical aspect of this valorization is the selection of microbial strain, and in this case study, cellulase producers use *Acinetobacter sp*. Meanwhile, the UV shield producer's internal business process is producing UV shields or sunscreens using the extraction method, utilizing SCG as primary source material.

The dynamics of interactions among the various actors within the EIP are visually conveyed through the depiction of material and data flows traversing individual swimlanes. A comprehensive summary of

Table 5: Material exchange between actors in coffee-based EIP Ketakasi

Interactions	Material exchange
Farmers–coffee firms/SMEs	Farmers send coffee hs to coffee firms/SMEs and receive payments from coffee firms/SMEs.
Farmers–Ketakasi cooperative	Farmers send coffee cherry/green beans/coffee pulp to the Ketakasi cooperative and receive payments from the cooperative.
Coffee firms/SMEs–Ketakasi cooperative	Coffee firms/SMEs send coffee pulp/SCG to the Ketakasi cooperative and receive payments from the cooperative.
Ketakasi cooperative–cellulase producer	The Ketakasi cooperative sends coffee pulp to a cellulase producer and receive payments from the cellulase producer.
Ketakasi cooperative–UV shield producer	Ketakasi cooperative sends SCG to a UV shield producer and receive payments from the UV shield producer.

these material exchange interactions is presented in Table 5 for a thorough understanding of the interrelationships. Material exchange processes within the EIP encompass the continuous transfer of data, as denoted by the dotted lines in Fig. 5. Notably, the Ketakasi coffee-based EIP design includes a mechanism for data integration via a "Data Store," which serves as a central database accessible to all actors within the EIP. This "Data Store" serves as a repository for crucial information related to transactions involving coffee pulp and SCG, encompassing details such as transaction quantities and the respective payments received by each actor, enhancing transparency and facilitating efficient information exchange among EIP participants. Information-sharing platforms benefit enterprises within EIP by increasing the awareness of CE and the implementation of IS (Wen *et al.*, 2018). The design of a coffee-based EIP in this study considering the material exchange within the EIP involves the flows of data and information among the EIP's participants. Compared with other manufacturing systems, an EIP possesses distinctive characteristics regarding the interactions within this park. The volume of data produced by each EIP participant is substantial and continually expanding, rendering conventional information management approaches impractical and ineffective for the management of EIP-related data. The development of "Data Store" in the EIP design is a solution to this need by becoming an information platform for data integration related to material exchange in the EIP. This finding aligns with previous studies indicating that the process of forming material exchange within EIP is through gathering and sharing relevant information among EIP's participants (Wangdi and Nepal, 2018). The cellulase producer and UV shield producer, responsible for the valorization of coffee waste, input aggregate demand data for coffee pulp and SCG, as well as their weekly distribution, into the "Data Store." This repository is accessible to all stakeholders within the EIP, including farmers and the coffee industry/SMEs. Farmers and the coffee industry/SMEs, who supply coffee pulp and SCG, deliver coffee waste to the Ketakasi cooperative and subsequently verify the compilation of data in the "Data Store." This platform enables farmers and the coffee industry/SMEs to track the extent to which their coffee pulp and SCG meet the set valorization quality standards. Accessible data include not only the quantities of materials exchanged but also the prenegotiated prices, allowing for an estimation of expected payments. In turn, cellulase and UV shield producers utilize the "Data Store" to monitor the actual supply against their operational forecasts and adjust production accordingly. The Ketakasi cooperative, functioning as the EIP's manager, oversees these material exchanges and manages financial transactions, issuing invoices based on the "Data Store" records. These invoices prompt payments to the cellulase and UV shield producers, which are then allocated to the respective farmers and coffee industry/SMEs as payment for their coffee pulp and SCG in accordance with the data recapitulation in the "Data Store." The Ketakasi cooperative employs the "Data Store" not only to ensure the management of material exchange quantities and financial transactions but also to uphold the quality assurance standards for the exchanged coffee by-products. The "Data Store" is crucial in this coffee-based EIP design and becomes an information platform fostering transparency and accessibility of information among EIP participants. This finding aligns with the interdependency relationship among participants within EIP that is explicitly specified on information bases, which presents the requirement for information platforms to bind scattered information as a whole (Zhou *et al.,* 2017). Implementing the "Data Store" facilitates data integration, thereby enhancing the ability of the Ketakasi cooperative to fulfill its responsibilities within the context of the EIP in an optimal manner. These data flows signify the importance of information and communication in facilitating efficient and coordinated material exchange (Boukhatmi *et al.*, 2023). Data integration and transparency enhance the predictability and reliability of material exchange processes and circularity toward CE (Bressanelli *et al.*, 2022). Within the EIP design, three pivotal gateways are integrated, defined as tasks encompassing regulations governing material exchange. These gateways include the automation screening by-product, the SCG gateway, and the coffee pulp gateway. The material exchange starts when farmers deliver coffee pulp to the Ketakasi cooperative warehouse after completing the pulping process. This delivery is conducted either on an individual basis or collectively, contingent upon the proximity and synchronicity of other farmers' delivery schedules. Coffee industries/SMEs deliver SCG after completing the production process. On average, the by-products from coffee processing total 308 tons of coffee pulp and 239 tons of SCG per week. Upon arrival, the Ketakasi cooperative undertakes a quality assessment of the coffee pulp, employing automated sorting gateways that evaluate parameters such as potential hydrogen (pH) levels and water content. The coffee pulp that conforms to the predefined criteria is then stored, while the noncompliant pulp is redirected for use in fertilizer and animal feed production facilitated by the cooperative. The Ketakasi cooperative delivers coffee pulp and SCG to cellulase producers and UV shield producers in alignment with the data collated in the "Data Store." Cellulase producers and UV shield producers utilize coffee pulp and SCG as raw materials for their production processes. The material exchange process operates continuously and dynamically in accordance with the business processes of each EIP participant. For IS optimization, the MILP mathematical model is employed. The subsequent section will provide an in-depth exploration of this optimization approach. In this study, the BPMN of coffee-based EIP in Ketakasi depicts closed-loop material flows to ensure that the waste from one actor becomes a valuable resource for another, facilitating circularity in material exchange (Piemonti *et al.*, 2023). For example, coffee pulp and SCG, which become waste for farmers and the coffee industry through material exchange in EIP, can become raw materials for cellulase producers and UV protector producers. The mutual benefit derived from this resource sharing not only minimizes waste but also reduces the need for resource extraction, thereby lowering the ecological footprint and resource depletion (Zhao *et al.*, 2023). This symbiotic relationship minimizes waste generation, encourages resource sharing, and exemplifies the tenets of a CE. The BPMN diagram in Fig. 5 depicts the actors, internal business processes, material and data exchanges, various actors' interdependence and critical roles in material exchanges, and value creation processes through valorization within the EIP. The cellulase and UV shield producers valorize coffee waste by producing valuable products. Their interest lies in securing a consistent supply of coffee waste materials, such as coffee pulp and SCG, to support their production processes. These processes contribute to environmental sustainability by reducing waste and offering economic benefits to actors engaged in the valorization process (Mendez-Alva *et al.*, 2021). The EIP design adds a new layer of economic and environmental sustainability by deriving value from materials that might otherwise be considered waste. The Ketakasi cooperative plays a multifaceted role as a manager of EIP. Their objectives encompass facilitating smooth material exchange among actors, ensuring the availability of resources for coffee by-product management, and promoting the overall sustainability and success of the EIP. An important role of the Ketakasi cooperative in material exchanges is to manage quality control on coffee pulp and SCG to enhance acceptance levels by the cellulase and UV shield producer. The Ketakasi cooperative has the motivation to maximize coffee by-products that can be valorized, namely, by encouraging farmers to conduct proper material handling and proper treatment of coffee pulp generated during coffee processing through various education and assistance. Assistance provided by the Ketakasi cooperative includes offering sensor facilities for pH and water content and arranging the scheduling of coffee pulp deliveries from farmers to meet the requirements of coffee waste users. The implication is that the Ketakasi cooperative not only helps farmers with waste management and reduces waste that is thrown directly into the environment but also provides economic benefits for farmers from the material exchange process.

Optimization of coffee waste exchange using the MILP mathematical model

The optimization of coffee waste exchange within an EIP offers substantial economic benefits, primarily through cost reductions and the creation of new revenue streams (Hamam *et al.*, 2023). Companies can significantly lower environmental costs linked to waste disposal, such as landfill fees and transportation costs, by repurposing coffee waste as a productive resource. The transformation of coffee waste into added-value products facilitates additional income. This reimagining of waste materials enhances operational efficiency and productivity, leading to increased profitability (Ledari *et al.*, 2023). The innovation spurred by the valorization of coffee waste can open up novel markets and business opportunities, particularly in the realm of sustainable goods, attracting further investment and fostering business expansion. Economic advantages also extend to compliance and supply chain sustainability. By optimizing waste exchange, businesses within the EIP can achieve regulatory compliance efficiently, avoiding potential fines and aligning with growing consumer demand for environmentally responsible practices. On the basis of the coffee-based EIP design, this study undertakes the optimization of coffee waste exchange to enhance the operational efficiency and functionality of the EIP. The coffee-based EIP design comprises three task gateways, which function as regulatory mechanisms governing material exchange. These gateways, namely, the “automation screening by-product gateway,” the “SCG gateway,” and the “coffee pulp gateway,” as shown in Fig. 5, play distinct and essential roles in the management of material exchange processes. Such gateways are strategically coordinated and managed by the Ketakasi cooperative. The “automation screening by-product gateway” serves as an automated sorting mechanism to determine whether coffee pulp is eligible for entry into the coffee by-product reservoir. This gateway has an automated sensor system, and specific criteria govern its decision-making process. The coffee pulp can pass through and access the coffee by-product reservoir if it exhibits a pH level of at least 5 and a minimum water content of 60%. These stringent criteria have been imposed because coffee pulp must meet precise pH and water content thresholds when intended for use as a raw material in the production of cellulase enzymes. When coffee pulp fails to meet these criteria during screening at this gateway, an alternative processing route is pursued, wherein the coffee pulp is directed toward animal feed and fertilizer production. The second gateway is the “coffee pulp gateway,” which regulates the flow of coffee pulp from the by-product reservoir to be sent to the cellulase producer. Within this gateway, the conveyance of coffee pulp to the cellulase producer is contingent upon meeting two specific criteria. First, the coffee pulp must have resided within the by-product reservoir for no longer than 3 days. Second, the quantity of coffee pulp supplied should align with, and not surpass, the predetermined weekly demand for coffee pulp, a figure established by the cellulase producer in alignment with the production plan. This planning, which is executed weekly, is instrumental in determining the requisite volume of coffee pulp necessary for the given production week. The final gateway is the “SCG gateway,” which manages the sending of SCG to the UV shield producer. The requirement for this gateway is that SCG can be sent to the UV shield producer as long as the supply does not exceed the aggregate demand for SCG for that week. The main objective of IS optimization in this study is to adopt the perspective of optimizing the value creation process within EIP by fostering a closed-loop production system (Prieto-Sandoval *et al.*, 2022). Optimization of value creation is conducted through maximization of the amount of value-added product through valorization technology. The optimization model is developed using the MILP mathematical model composed of objective function, decision variables, and constraints (Wolsey, 2020). The objective function is considered to obtain the optimum solution for the maximum amount of valorized coffee pulp and SCG, which has implications for minimizing coffee waste disposed into the environment, resulting in the reduction of environmental costs. The objective function of the MILP optimization model is subject to the constraints of the three gateway material exchange rules described previously. The MILP optimization model is

Table 6: Set of subscripts and variables in the MILP model

Set	Definition
Subscript	
i	Index for week-*i*
Variables	
x_i	Coffee pulp collected for week-*i* (ton)
y_i	Coffee pulp valorized into cellulase for week-*i* (ton)
z_i	SCG valorized into UV shield for week-*i* (ton)
w_i	Coffee pulp send to animal feed and fertilizer plant for week-*i* (ton)
a_i	A binary variable, 1 if the pH minimum is 5; 0 otherwise
b_i	A binary variable, 1 if the water content minimum is 0.6; 0 otherwise
c_i	A binary variable, 1 if the maximum coffee pulp shelf life in the reservoir is 3 days; 0 otherwise
n_i	pH x_i
m_i	Water content x_i
p_i	Shelf life of coffee pulp in the reservoir (days)
Dc_i	Demand aggregate of coffee pulp for week-*i*
Ds_i	Demand aggregate of SCG for week-*i*

implemented through an inclusive material exchange design involving interdependence and mutual influence between farmers, the coffee industry, the Ketakasi cooperative, the cellulase producer, and the UV shield producer. The optimum value creation solution in this model is achieved when each actor in the EIP acquires adequate economic benefits from the material exchange process (Huong, 2023). The optimization MILP model is completed using Solver in MS Excel to obtain the optimum solution. The set of subscripts and variables used in the MILP mathematical model is summarized in Table 6.

The objective function of the optimization model employed in this study is to maximize the valorization of coffee waste into value-added products. More precisely, the goal is to maximize the valorization of coffee pulp into cellulase enzymes and SCG into UV shields by using Eq. 1 (Kantor *et al.*, 2020).

Objective function:

$$\text{Max Z} = \sum_{i=1}^{n} (ai.bi).xi + ci.yi + zi + wi \quad (1)$$

The constraint imposed on the “gateway automation screening by-product” necessitates that, for passing into the coffee by-product reservoir, the coffee pulp must exhibit a minimum pH of 5, as specified in Eq. 2, and have a water content of no less than 60%, as indicated in Eq. 3; Eqs. 2 and 3 are developed on the basis of previous research on cellulase production valorized from coffee pulp (Selvam *et al.*, 2014).

Subject to constraint:

$$\text{IF } n_i \geq 5 \text{ THEN } a_i = 1, \text{ ELSE } a_i = 0 \quad (2)$$
$$1 \leq n_i \leq 14$$

$$\text{IF } m_i \geq 0.6 \text{ THEN } b_i = 1, \text{ ELSE } b_i = 0 \quad (3)$$
$$m_i \geq 0$$

The constraint governing the “gateway coffee pulp” states that coffee pulp sourced from the Ketakasi cooperative will be delivered to cellulase producers under the conditions that the coffee pulp’s shelf life in the reservoir does not exceed 3 days, as stipulated in Eq. 4 developed with reference to (Saldana-Mendoza *et al.*, 2021), and the quantity of coffee pulp supplied does not surpass the aggregate demand for that particular week, as indicated in Eq. 5 (Wolsey, 2020). Meanwhile, the “gateway SCG” constraint indicates that SCG can be sent to the UV shield producer if the amount of SCG supply does not exceed the aggregate demand for that week, as shown in Eq. 6 (Kanlayavattanakul *et al.*, 2021).

$$\text{IF } p_i \leq 3 \text{ THEN } c_i = 1, \text{ ELSE } c_i = 0 \quad (4)$$
$$p_i \geq 0$$

$$y_i \leq Dc_i \quad (5)$$
$$Dc_i \geq 0$$

$$z_i \leq Ds_i \quad (6)$$
$$Ds_i \geq 0$$

Eq. 7 (Wolsey, 2020) defines the capacity constraint of the coffee by-product reservoir, imposing a limitation such that the combined storage of coffee pulp and SCG in a given week should not exceed 520 tons.

$$x_i + z_i \leq 520 \quad (7)$$

Subject to constraint:

$Eqx_i \geq 0$

$z_i \geq 0$

Eq. 8 represents a logical constraint, specifying that the quantity of coffee pulp valorized and the amount directed toward the animal feed and fertilizer plant must not surpass the initial amount of coffee pulp collected (Wolsey, 2020)

$$w_i + y_i \leq x_i \quad (8)$$

$w_i \geq 0,\ y_i \geq 0,\ x_i \geq 0$

The validation of the MILP optimization model in this study is conducted by optimality gap analysis. The optimality gap quantifies the difference between the current best solution and the best-known upper bound for the maximization problem or lower bound for the minimization problem on the optimal solution. The optimality gap is a measure of how far the current solution is from the best possible solution. This gap is typically expressed as a percentage and is calculated for maximization problems using Eq. 9 (Shekeew and Venkatesh, 2023).

$$\text{Optimality Gap} = \frac{\text{Upper bound} - \text{Curent optimum solution}}{\text{Upper bound}} x100\% \quad (9)$$

The optimization model is then completed using data collected over a period of 5 months of observations in the case study. The optimization objective function is completed using Solver in MS Excel, and the result is presented in Fig. 6. The optimization result presented in Fig. 6 depicts a comparison between the actual coffee waste generated and the potential waste amenable to valorization within the EIP, encompassing coffee pulp and SCG. Coffee pulp and SCG generated for 21 weeks show fluctuations every week. Coffee processing in Ketakasi generates 252–376 tons of coffee pulp per week and 181–317 tons of SCG per week, as depicted in a blue graph in Fig. 6. The MILP model optimization results are shown in an orange graph, which represents the optimum amount of valorized coffee pulp and valorized SCG each week. Fig. 6 compares the optimum amount of valorized coffee pulp and the total coffee pulp generated, as well as the optimum amount of valorized SCG and the total SCG generated. The average amount of coffee pulp generated from coffee processing is 308 tons per week, while the average optimization result for the amount of valorized coffee pulp is 72.3% at 224 tons per week. This MILP optimization model is validated using Eq. 9, and an optimality gap of 9.67% is obtained. This percentage of optimality gap implies that the current optimum solution's valorized coffee waste is 9.67% less than the best-known upper bound on the maximum valorized coffee waste that could potentially be achieved. The optimization results show that not all coffee pulp can be valorized into cellulase enzymes and processed into fertilizer and animal feed. Likewise, the average amount of SCG generated is 239 tons per week, while the average optimization result for the amount of valorized SCG is 164 tons per week or approximately 68.5%; the remainder is

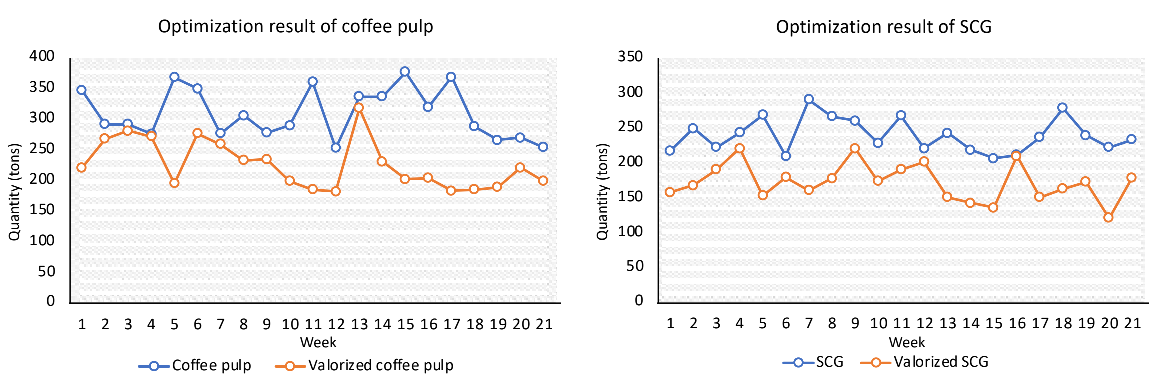

Fig. 6: Optimization result of material exchange for coffee pulp and SCG

disposed of into the environment. The comparison result indicates that material exchange in coffee-based EIP is capable of facilitating the value creation process. A total of 72.3% of coffee pulp is valorized into cellulase enzymes, and 68.5% of SCG is valorized into UV shield, which illustrates the value creation process. Coffee pulp and SCG, which are initially by-products with no economic value and causes emissions, undergo a valorization transformation into cellulase enzymes and UV shields with economic added value. Valorization of coffee pulp and SCG shows that the EIP design is also capable of facilitating IS optimization, in which by-products from farmers and coffee SME/industries become raw materials for cellulase and UV shield producers (Noori *et al.*, 2023). In this study, cellulase producers have a tendency to increase their production capacity with the intention of increasing the amount of coffee pulp demand. The relatively low price of coffee pulp compared with that of the original raw material is the main motivation for cellulase producers. This condition demonstrates the interdependence among EIP stakeholders with disparate interests, ultimately influencing the overall performance of the EIP, particularly with respect to optimizing material exchange and enhancing value through valorization (Bastias *et al.*, 2023). The MILP optimization model in this study is inclusive, in which every coffee by-product producer and processor receive economic benefits as an outcome of the material exchange process. Farmers and coffee industries, which are the coffee pulp and SCG producers, receive payments from the material exchanges. The inclusive MILP optimization model in this study facilitates payment agreement of coffee by-products between farmers and SMEs/coffee industry with cellulase and UV shield producers through the intermediary Ketakasi cooperative as EIP manager. This finding contributes to providing an appropriate scheme for a proper benefit for all participants in EIP, considering that in EIP practices, the greatest plants are usually the ones that obtain the highest benefits (Juarez-Garcia *et al.*, 2020). Meanwhile, cellulase producers and UV shield producers acquire access to cheap raw materials. This finding strengthens previous studies indicating that the competitive price factor of raw materials originating from by-products is one of the determinants in optimizing IS in EIP (Huang *et al.*, 2020). The percentage of valorized coffee pulp and valorized SCG shows a reduction in coffee solid waste disposed into the environment, resulting in decreased environmental impacts.

The discrepancy between the aggregate generation of coffee solid waste and the optimized valorization outcomes signifies the proportion of coffee solid waste designated for conversion into fertilizer and animal feed. This disparity highlights the existing opportunities for enhancing value creation in the advancement of EIP. Various factors, including coffee pulp failing the screening criteria associated with pH and water content, contribute to this disparity. Should coffee pulp fail to conform to the specified pH and water content criteria, farmers can pursue improvements as the main producers of coffee pulp. Farmers can implement various alternative improvements, such as refining the post-production material handling of coffee pulp and optimizing the scheduling of coffee pulp deliveries to the Ketakasi cooperative. The strong motivation among farmers to enact these improvements stems from the prospect of realizing augmented income by adhering to the cellulase producer's requirements regarding pH and water content. This finding underscores the influential role of material exchange within the EIP, fostering a climate that incentivizes and propels internal business process adjustments among the key actors in the EIP (Komkova and Habert, 2023). The interdependence observed among the actors within the EIP underscores the complexity of managing diverse interests while striving for the collective goal of enhancing the EIP's performance. This disparity is also caused by the constrained valorization of coffee pulp and SCG due to the production capacity of cellulase and UV shields, as limited by the weekly aggregate demand for coffee pulp and SCG. Increasing the production capacity of cellulase and UV shield potentially increases the valorization process and reduces the solid waste disparity. Another alternative is adding flow material exchange to produce new valorization products aside from cellulase and UV shields. This step can be realized by adding actors to the EIP who function as coffee pulp and SCG processors, but this alternative requires an investment decision. The findings presented in this paper unveil a structured approach to enhancing the operational efficiency and overall functionality of an EIP regarding coffee waste valorization. Through the BPMN and subsequent optimization of the EIP, this study elucidates a framework that effectively manages material exchange and value creation processes, contributing to environmental sustainability and economic value creation. The environmental impact is decreased owing to reduced disposal of coffee pulp and SCG directly into the environment. This study identifies an increase in coffee pulp valorization from 15% to 72.3% and SCG from unvalorized to 68.5% valorization. The percentage of valorized coffee pulp and SCG also represents a reduction in the percentage of coffee solid waste that is disposed of into the environment. This reduction in solid waste disposal will have an impact on reducing waste landfills, soil pollution, eutrophication, and other related environmental impacts. Environmental benefits also result from the low raw material consumption for cellulase and UV shield production. This condition complies with the reuse of coffee by-products recovered and optimizes natural resource use through the circulation of high-utility materials. The environmental benefits also include a decrease in hazards to the environment, especially in terms of waste disposal and emission of GHG caused by coffee solid waste. The implication is a reduction in environmental costs that must be borne by the coffee agroindustry. These resultant environmental benefits will enhance the environmental sustainability of the Ketakasi coffee agroindustry and its surroundings. This finding aligns with previous studies on the implementation of EIP, raising environmental benefits primarily from the reduction of pollutant emissions to the environment and the exploitation of raw materials from natural resources (Kowalski *et al.*, 2023). This study identifies challenges in implementing IS within the coffee-based EIP. The first challenge is the difficulty in developing the coffee waste valorization industries/SMEs. The development of the coffee waste valorization industry requires institutional settings and investment decisions (Maryev and Smirnova, 2021). An alternative solution for this challenge can be developed through public–private partnerships involving local government and private industry, such as offering incentives for companies that use coffee waste raw materials for their production. The second challenge is the existence of a trust issue between EIP participants because by carrying out material exchange in the EIP, these companies must share sensitive company information related to their production processes. Alternative solutions that can be implemented are establishing a company confidentiality agreement or developing a subsidiary as a coffee waste processor so that trust can be achieved in a way that company secrets will be protected. Based on the findings in this study, several practical recommendations emerge for stakeholders, policymakers, and practitioners in the domain of EIP development. For stakeholders, the pivotal role of a central management entity, as exemplified by the Ketakasi cooperative, cannot be overstated; such an entity should be instituted to steer material exchanges and oversee EIP operations. The success of an EIP is inextricably linked to the strength of its information and communication infrastructure. Thus, stakeholders must prioritize the establishment of robust networks that enable seamless sharing and coordination. For practitioners, the application of structured mathematical models, such as the MILP model deployed in the study, should be replicated to enhance the valorization process, thereby contributing to the EIP's sustainability and economic viability. Practitioners must engage in meticulous planning and management to adeptly navigate the complexities of production demands within an EIP framework. For policymakers, the findings in this study contribute to developing regional planning policies and regulations toward CE through the development of EIP. For future EIP designs, this study illustrates the potential of EIPs to maximize the value creation process by applying the MILP mathematical model to optimize the valorization of coffee waste. This structured approach to managing material exchange processes contributes to environmental sustainability and economic value creation, providing a strategic framework that can be adapted to future EIP designs in various sectors.

CONCLUSION

This study has comprehensively analyzed and formulated a coffee-based EIP design in Ketakasi, utilizing BPMN within a systems engineering framework. The BPMN diagram illustrates the EIP design and presents the actors, internal business processes, material and data exchanges, various actors' interdependence and critical roles in material exchanges, and value creation processes using valorization within EIP. The role of the Ketakasi cooperative as a facilitator of material exchange and manager of the EIP is pivotal. The use of a "Data Store" for data integration enhances the transparency and efficiency of information exchange among EIP participants, promoting predictability and reliability in material exchange. This research underscores the importance of information and communication in the success of EIPs, ensuring the sustainable management of resources and materials. The cellulase producer and UV shield producer's valorization of coffee waste sets an example of how resource sharing can lead to economic benefits and reduced waste, aligning with the principles of a CE. The application of the MILP mathematical model has provided a structured approach to maximizing the valorization of coffee waste into value-added products, specifically cellulase enzymes and UV shields. The objective function seeks to optimize this valorization, ultimately contributing to reducing coffee waste disposal into the environment. A total of 72.3% of coffee pulp is valorized into cellulase enzymes, and 68.5% of SCG is valorized into UV shield, which illustrates the value creation process. This study emphasizes the interconnectedness of the EIP stakeholders and their diverse interests. The success of material exchange within the EIP is contingent on the rigorous criteria set for coffee pulp and SCG and the weekly production planning and capacity of the cellulase and UV shield producers. This interdependence emphasizes the complexity of managing diverse interests while collectively striving to enhance the EIP's performance. This paper presents a structured framework for efficiently managing material exchange processes within an EIP, contributing to environmental sustainability and economic value creation. By optimizing coffee waste exchange, this study demonstrates the potential of EIPs to minimize waste and enhance resource valorization, thus aligning with the principles of a CE and promoting the responsible management of valuable resources. This study contributes to the knowledge gap in the literature by developing an inclusive EIP design that facilitates the optimization of the value creation process through valorization technology. Based on the findings in this study, several practical recommendations emerge for stakeholders, policymakers, and practitioners in the domain of EIP development.

AUTHOR CONTRIBUTIONS

N. Laili contributed to data collection, field observation, EIP design, MILP modeling, and manuscript preparation and revision. T. Djatna, the corresponding author, contributed to improving the EIP design, supervised MILP modeling, and enriched the discussion. N.S. Indrasti supervised the data collection and analysis, oversaw the manuscript preparation, improved the EIP design, and enriched the discussion. M. Yani supervised the data collection and analysis, oversaw the manuscript preparation, proofread the manuscript, and enriched the discussion.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
BPMN	Business Process Model and Notation
BPS	Badan Pusat Statistik
BRIN	Badan Riset dan Inovasi Nasional
°C	Degree Celsius
CE	Circular economy
EIP	Eco-industrial park
Eq.	Equation
GDP	Gross domestic product
GHG	Greenhouse gas
ha	Hectares
hs	Hard skin
ILP	Integer linear programming
individuals	Individuals
IS	Industrial symbiosis
kg	Kilogram
km	Kilometer
km²	Square kilometers
masl	Meters above sea level
Max	Maximization
Million	Million
MILP	Mixed-integer linear programming
mm	Millimeters
MINLP	Mixed-integer nonlinear programming
months	Months
MS Excel	Microsoft Excel
pH	Potential hydrogen
SAP	System application and product in processing
SCG	Spent coffee grounds
SMEs	Small- and medium-sized enterprises
sp.	Species
SSF	Solid-state fermentation
Ton	Ton
Tons	Tons
UML	Unified modeling language
UV	Ultraviolet
Week	Week

REFERENCES

Afshari, H.; Farel, R.; Peng, Q., (2018). Challenges of value creation in eco-industrial parks (EIPs): a stakeholder perspective for optimizing energy exchanges. Resour. Conserv. Recycl., 139: 315-325 **(11 pages)**.

Afshari, H.; Tosarkani, B.M.; Jaber, M.Y.; Searcy, C., (2020). The effect of environmental and social value objectives on optimal design in industrial energy symbiosis: a multi-objective approach. Resour. Conserv. Recycl., 158: 104825 **(19 pages)**.

Arya, S.S.; Venkatram, R.; More, P.R.; Vijayan, P., (2022). The wastes of coffee bean processing for utilization in food: a review. J. Food Sci. Technol., 59(2): 429–444 **(16 pages)**.

Aussel, D.; Van, K.C.; Salas, D., (2023). Optimal design of exchange water networks with control inputs in eco-industrial parks. Energy Econ., 120: 106480 **(16 pages)**.

Bai, C.; Sarkis, J.; Yin, F.; Dou, Y., (2019). Sustainable supply chain flexibility and its relationship to circular economy-target performance. Int. J. Prod. Res., 58(19): 1-19 **(19 pages)**.

Bastias, F.A.; Rodriguez, P.D.; Arena, A.P.; Peiro, L.T., (2023). Measuring the symbiotic performance of single entities within networks using an LCA approach. J. Environ. Chem. Eng., 11(5): 111023 **(10 pages)**.

Belaud, J.-P.; Adoue, C.; Vialle, C.; Chorro, A.; Sablayrolles, C., (2019). A circular economy and industrial ecology toolbox for developing an eco-industrial park: perspectives from French policy. Clean Technol. Environ. Policy., 21(5): 967–985 **(19 pages)**.

Blinová, L.; Sirotiak, M., (2019). Utilization of spent coffee grounds for removal of hazardous substances from water: a review. Research Paper Faculty of Materials Science and Technology Sloak University of Technology, 27(44): 145-152 **(8 pages)**.

Boix, M.; Montastruc, L.; Azzaro-Pantel, C.; Domenech, S., (2015). Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod., 87: 303–317 **(15 pages)**.

Boukhatmi, A.; Nyffenegger, R.; Grosser, S.N., (2023). Designing a digital platform to foster data-enhanced circular practices in the European solar industry. J. Clean. Prod., 418: 137992 **(13 pages)**.

BPS Indonesia, (2022). Indonesia coffee statistics 2021. BPS Indonesia.

Bressanelli, G.; Adrodegari, F.; Pigosso, D.C.A.; Parida, V., (2022). Towards the smart circular economy paradigm: a definition, conceptualization, and research agenda. Sustainability, 14(9): 4960 **(20 pages)**.

Capanoglu, E.; Nemli, E.; Tomas-Barberan, F., (2022). Novel approaches in the valorization of agricultural wastes and their applications. J. Agric. Food Chem., 70(23): 6787–6804 **(18 pages)**.

Chala, B.; Oechsner, H.; Latif, S.; Müller, J., (2018). Biogas potential of coffee processing waste in Ethiopia. Sustainability. 10(8): 1-14 **(14 pages)**.

Chen, Y.; Chen, Y.; Yin, G.; Liu, Y., (2023). Industrial eco-efficiency of resource-based cities in China: spatial–temporal dynamics and associated factors. Environ. Sci. Pollut. Res., 30(41): 94436-94454 **(19 pages)**.

Demartini, M.; Tonelli, F.; Govindan, K., (2022). An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda. Clean. Logist. Supply Chain, 3: 100020 **(11 pages)**.

Devanand, A.; Karmakar, G.; Krdzavac, N.; Rigo-Mariani, R.; Eddy, Y.S.F.; Karimi, I.A.; Kraft, M., (2020). Ontopowsys: a power system ontology for cross-domain interactions in an eco-industrial park. Energy. 1: 100008 **(18 pages)**.

Domenech, T.; Bleischwitz, R.; Doranova, A.; Panayotopoulos, D.; Roman, L., (2019). Mapping industrial symbiosis development in Europe – typologies of networks, characteristics, performance and contribution to the circular economy. Resour. Conserv. Recycl., 141: 76-98 **(23 pages)**.

Durán-Aranguren, D.D.; Robledo, S.; Gomez-Restrepo, E.; Valencia, J.W., (2021). Scientometric overview of coffee by-products and their applications. Molecules. 26(7605): 1-25 **(25 pages)**.

ElMassah, S., (2018). Industrial symbiosis within eco-industrial parks: sustainable development for Borg El-Arab in Egypt. Bus. Strateg. Environ., 27(7): 884-892 **(8 pages)**.

Fan, Y.; Qiao, Q.; Xian, C.; Xiao, Y.; Fang, L., (2017). A modified ecological footprint method to evaluate environmental impacts of industrial parks. Resour. Conserv. Recycl., 125: 293-299 **(7 pages)**.

Farooque, M.; Zhang, A.; Liu, Y.; Hartley, J.L., (2022). Circular supply chain management: performance outcomes and the role of eco-industrial parks in China. Transp. Res. Part E., 157: 102596 **(20 pages)**.

Fraccascia, L.; Yazan, D.M., (2018). The role of online information-sharing platforms on the performance of industrial symbiosis networks. Resour. Conserv. Recycl., 136: 473-485 **(13 pages)**.

Galvan-Cara, A.; Graells, M.; Espuna, A., (2022). Application of industrial symbiosis principles to the management of utility networks. Appl. Energy. 305: 117734 **(15 pages)**.

Genc, O.; Kurt, A.; Yazan D.M.; Erdis, E., (2020). Circular eco-industrial park design inspired by nature: an integrated non-linear optimization, location, and food web analysis. J. Environ. Manage., 270: 110866 **(13 pages)**.

Ghisellini, P.; Ripa, M.; Ulgiati, S., (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod., 178: 618-643 **(25 pages)**.

Giraldi-Díaz, M.R.; Medina-Salas, L.; Castillo-González, E.; León-Lira, R., (2018). Environmental impact associated with the supply chain and production of grounding and roasting coffee through life cycle analysis. Sustainability. 10(12): 1-17 **(17 pages)**.

Hamam, M.; Spina, D.; Raimondo, M.; Di Vita, G.; Zanchini, R.; Chinnici, G.; Tóth, J.; D'Amico, M., (2023) Industrial symbiosis and agri-food system: themes, links, and relationships. Front. Sustain. Food Syst., 6:1012436 **(20 pages)**.

Hu, W.; Tian, J.; Li, X.; Chen, L., (2020). Wastewater treatment system optimization with an industrial symbiosis model: a case study of a Chinese eco-industrial park. J. Ind. Ecol., 24(6): 1338-1351 **(14 pages)**.

Huang, L.; Zhen, L.; Yin, L., (2020). Waste material recycling and exchanging decisions for industrial symbiosis network optimization. J. Clean. Prod., 276: 124073 **(15 pages)**.

Huong, T.T., (2023). Assessment of eco-industrial park (EIP) performance at the preliminary step in Vietnam. Curr. Appl. Sci. Technol., 23(6): 1-17 **(17 pages)**.

Jing, R.; Li, Y.; Wang, M.; Chachuat, B.; Lin, J.; Guo, M., (2021). Coupling biogeochemical simulation and mathematical optimisation towards eco-industrial energy systems design. Appl. Energy. 290: 116773 **(16 pages)**.

Juarez-Garcia, M.; Munguia-Lopez, A.C.; Ponce-Ortega, J.M., (2020). Optimization approach to identify fair solutions in the synthesis of carbon, hydrogen, and oxygen symbiosis networks. Ind. Eng. Chem. Res., 59(13): 5985-5995 **(11 pages)**.

Kanlayavattanakul, M.; Lourith, N.; Chaikul, P., (2021). Valorization of spent coffee grounds

as the specialty material for dullness and aging of skin treatments. Chem. Biol. Technol. Agric., 8(55): 1-12 **(12 pages)**.

Kantor, I.; Jean-Loup, R.; Hur, B.; Francois, M., (2020). A mixed-integer linear programming formulation for optimizing multi-scale material and energy integration. Front. Energy Res., 8(49): 1-20 **(20 pages)**.

Kastner, C.A.; Lau, R.; Kraft, M., (2015). Quantitative tools for cultivating symbiosis in industrial parks: a literature review. Appl. Energy., 155: 599-612 **(13 pages)**.

Kirchherr, J.; Reike, D.; Hekkert, M., (2017). Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl., 127: 221-232 **(11 pages)**.

Komkova, A.; Habert, G., (2023). Optimal supply chain networks for waste materials used in alkali-activated concrete fostering circular economy. Resour. Conserve. Recycl., 193: 106949 **(11 pages)**.

Kowalski, Z.; Kulczycka, J.; Makara, A.; Mondello, G.; Salomone, R., (2023). Industrial symbiosis for sustainable management of meat waste: the case of ´Smiłowo eco-industrial park, Poland. Int. J. Environ. Res. Public Health. 20(6): 5162 **(22 pages)**.

Laili, N.; Indrasti, N.S.; Wahyudi, D., (2022). Design of sustainable coffee processing wastewater treatment system using k-means clustering algorithm. IOP Conf. S.: Earth Environ. Sci., 1063(1): 012032 **(7 pages)**.

Lawal, M.; Alwi, S.R.W.; Manan, Z.A.; Ho, W.S., (2021). Industrial symbiosis tools - a review. J. Clean. Prod., 280 (1): 124327 **(20 pages)**.

Ledari, M.B.; Saboohi, Y.; Azamian, S., (2023). Water-food-energy-ecosystem nexus model development: resource scarcity and regional development. Energy Nexus, 10: 100207 **(16 pages)**.

Liberona, G.; Di Pretoro, A.; Negny, S.; Montastruc, L.; Salas, D., (2023). Robustness in optimal design of Eco-Industrial Parks under the lens of two-stage stochastic optimization. Comp. Chem. Eng., 179: 108399 **(12 pages)**.

Liu, W.; Tian, J.; Chen, L.; Lu, W.; Gao, Y., (2015). Environmental performance analysis of eco-industrial parks in China: A data envelopment analysis approach. J. Ind. Ecol., 19(6): 1070–1081 **(11 pages)**.

Martins, R.P.; Lopes, N.; Santos, G., (2019). Improvement of the food hygiene and safety production process of a not-for-profit organization using business process model and notation (BPMN). Procedia Manuf., 41: 351-358 **(8 pages)**.

Maryev, V.A.; Smirnova, T.S., (2021). Perspective of CE in Russia:

from theory to practice. In: Circular Econ.: Rec. Trends Glob. Perspect. 259-279 **(21 pages)**.

Mendez-Alva, F.; Cervo, H.; Krese, G.; Eetvelde, G.V., (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. J. Clean. Prod., 314: 128031 **(18 pages)**.

Misrol, M.S.; Wan Alwi, S.R.; Lim, J.S.; Manan, Z.A., (2022). Optimising renewable energy at the eco-industrial park: a mathematical modelling approach. Energy, 261(B): 125345 **(14 pages)**.

Mousque, F.; Boix, M.; Montastruc, L.; Domenech, S.; Negny, S., (2020). Optimal design of eco-industrial parks with coupled energy networks addressing complexity bottleneck through an interdependence analysis. Comput. Chem. Eng., 138: 106859 **(16 pages)**.

Neri, A.; Butturi, M.A.; Lolli, F.; Gamberini, R., (2023). Inter-firm exchanges, distributed renewable energy generation, and battery energy storage system integration via microgrids for energy symbiosis. J. Clean. Prod., 414: 137529 **(17 pages)**.

Neves, A.; Godina, R.; Azevedo, S.G.; Matias, J.C.O., (2020). A comprehensive review of industrial symbiosis. J. Clean. Prod., 247: 119113 **(21 pages)**.

Nguyen, Q.A.; Cho, E.J.; Lee, D.S.; Bae, H.J., (2019). Development of an advanced integrative process to create valuable biosugars including manno-oligosaccharides and mannose from spent coffee grounds. Bioresour. Technol., 272(1): 209-216 **(8 pages)**.

Noori, S.; Korevaar, G.; Stikkelman, R.; Ramirez, A., (2023). Exploring the emergence of waste recovery and exchange in industrial clusters. J. Ind. Ecol., 27 (3): 937-950 **(13 pages)**.

Ormazabal, M.; Prieto-sandoval, V.; Puga-Leal, R.; Jaca, C., (2018). Circular economy in Spanish SMEs: challenges and opportunities. J. Clean. Prod., 185: 157-167 **(11 pages)**.

Perrucci, D.V.; Aktas, C.B.; Sorentino, J.; Akanbi, H.; Curabba, J., (2022). A review of international eco-industrial parks for implementation success in the United States. City Environ. Interact., 16: 100086 **(14 pages)**.

Piemonti, A.; Conforti, A.; Cominoli, L.; Luciano, A.; Plizzari, G.; Sorlini, S., (2023). Exploring the potential for steel slags valorization in an industrial symbiosis perspective at meso-scale level. Waste Biomass Valorization., 14(10): 3355-3375 **(21 pages)**.

Prieto-Sandoval, V.; Mejia-Villa, A.; Jaca, C.; Ormazabal, M., (2022). The case of an agricultural crop business association in Navarra as circular economy intermediary. Circ. Econ. Sustain., 2(2): 713-729 **(17 pages)**.

Ribeiro, P.; Fonseca, F.; Neiva, C.; Bardi, T.; Lourenço, J.M., (2018). An integrated approach towards transforming an industrial park into an eco-industrial park: the case of Salaise-Sablons. J. Environ. Plan. Manag., 61(2): 195–213 **(18 pages)**.

Ruslin, R.; Mashuri, S.; Rasak, M.S.A.; Alhabsyi, F.; Syam, H., (2022). Semi-structured interview: a methodological reflection on the developmet of a qualitative research instrument in educational studies. IOSR J. Res. Meth. Educ., 12(1): 22-29 **(8 pages)**.

Sahana, M.; Srikantha, H.; Mahesh, S.; Mahadeva, S.M., (2018). Coffee processing industrial wastewater treatment using batch electrochemical coagulation with stainless steel and Fe electrodes and their combinations, and recovery and reuse of sludge. Water Sci. Technol., 78(2): 279-289 **(10 pages)**.

Saldana-Mendoza, S.A.; Ascacio-Valdes, J.A.; Palacios-Ponce, A.S.; Contreras-Esquivel, J.C.; Rodriguez-Herrera, R.; Ruiz, H.A.; Martinez-Hernandez, J.L.; Sugathan, S.; Aguilar, C.N., (2021). Use of wastes from the tea and coffee industries for the production of cellulases using fungi isolated from the western ghats of India. Syst. Microbiol. Biomanuf., 1(1): 33-41 **(9 pages)**.

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages)**.

Santos, E.M.; de Macedo, L.M.; Tundisi, L.L.; Ataide, J.A.; Camargo, G.A.; Alves, R.C.; Oliveira, M.B.P.; Mazzola, P.G., (2021). Coffee by-products in topical formulations: a review. Trends Food Sci. Technol., 111(1): 280–291 **(11 pages)**.

Schaffer, E.; Stiehl, V.; Schwab, P.K.;Mayr, A.; Lierhammer, J.; Franke, J., (2021). Process-driven approach within the engineering domain by combining business process model and notation (BPMN) with process engines. Proceedia CIRP, 96: 207-212 **(6 pages)**.

Selvam, K.; Govarthanan, M.; Kamala-Kannan, S.; Govindharaju, M.; Senthilkumar, B.; Selvankumar, T.; Sengottaiyan, A., (2014). Process optimization of cellulase production from alkali-treated coffee pulp and pineapple waste using Acinetobacter sp. TSK-MASC. RSC Adv., 24(4): 13045-13051 **(7 pages)**.

Shekeew, M.I.A.; Venkatesh, B., (2023). Learning-assisted variables reduction method for large-scale MILP unit commitment. IEEE Open Access J. Power Energy., 10: 245-258 **(14 pages)**.

Shen, N.; Peng, H., (2021). Can industrial agglomeration achieve the emission-reduction effect? Soc. Econ. Plan. Sci., 75: 100867 **(12 pages)**.

Sivakumar, D.; Srikanth, P.; Ramteke, P.W.; Nouri, J., (2022). Agricultural waste management generated by agro-based industries using biotechnology tools. Global J. Environ. Sci. Manage., 8(2): 281-296 **(16 pages)**.

Stucki, J.; Flammini, A.; van Beers, D.; Phuong, T.T.; Anh, N.T.; Dong, T.D.; Huy, V.Q.; Hieu, V.T.M., (2019). Eco-industrial park (EIP) development in Vietnam: result and key insights from UNIDO's EIP project (2014-2019). Sustainability, 11(17): 4667 **(23 pages).**

Tiu, B.T.C.; Cruz, D.E., (2017). An MILP model for optimizing water exchanges in eco-industrial parks considering water quality. Resour. Conserv. Recycl., 119: 89-96 **(8 pages)**.

Tolstykh, T.; Shmeleva, N.; Gamidullaeva, L.; Krasnobaeva, V., (2023). The role of collaboration in the development of industrial enterprise integration. Sustainability, 15(9): 7180 **(26 pages)**.

Tumilar, A.S.; Milani, D.; Cohn, Z.; Florin, N.; Abbas, A., (2021). A modelling framework for the conceptual design of low-emission eco-industrial parks in the circular economy: a case for algae-centered business consortia. Water., 13(1): 69 **(24 pages)**.

Valenzuela-Venegas, G.; Salgado, J.C.; Díaz-Alvarado, F.A., (2016). Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. J. Clean. Prod., 133: 99-116 **(17 pages)**.

Ventura, V.; Bortolini, M.; Galizia, F.G.; Mora, C., (2023). Industrial symbiosis network optimization model for supporting by-products reuse. CARV 2023: Production processes and product evolution in the age of disruption: 432-441 **(10 pages)**.

Wangdi, S.C.; Nepal, M.P., (2018). Towards the development of eco-industrial estates in Bhutan. Proc. Inst. Civ. Eng. Eng. Sustain., 171 (7): 368-379 **(12 pages)**.

Wasson, C.S., (2015). System engineering analysis, design, and development: concepts, principles, and practices. 1st ed. Wiley.

Wen, Z.; Hu, Y.; Lee, J.C.K.; Luo, E.; Li, H.; Ke, S., (2018). Approaches and policies for promoting industrial park recycling transformation (IPRT) in China: practices and lessons. J. Clean. Prod., 172: 1370-1380 **(11 pages)**.

Winans, K.; Kendall, A.; Deng, H., (2017). The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev., 68: 825–833 **(8 pages)**.

Woldesenbet, A.G.; Woldeyes, B.; Chandravanshi, B.S., (2016). Bio-ethanol production from wet coffee processing waste in Ethiopia. SpringerPlus. 5(1): 1-7 **(7 pages)**.

Wolsey, L., (2020). Integer programming. Wiley and Sons.

Yu, H.; Da, L.; Li, Y.; Chen, Y.; Geng, Q.; Jia, Z.; Zhang, Y.; Li, J., (2023). Industrial symbiosis promoting material exchanges in Ulan Buh demonstration eco-industrial park: A multi-objective MILP model. J. Clean. Prod., 414: 137578 **(14 pages)**.

Yu, Y.; Yazan, D.M.; Bhochhibhoya, S.; Volker, L., (2021). Towards circular economy through industrial symbiosis in the Dutch construction industry: a case of recycled concrete aggregates. J. Clean. Prod., 293: 126083 **(15 pages)**.

Zhao, Y.; Yu, M.; Xiang, Y.; Chang, C., (2023). An approach to stimulate the sustainability of an eco-industrial park using coupled emergy and system dynamics. Environ. Dev. Sustain., 25(10): 11531-11556 **(25 pages)**.

Zhou, L.; Zhang, C.; Karimi, I.A.; Kraft, M., (2017). J-park simulator, an intelligent system for information management of eco-industrial parks. Energy Procedia, 142: 2953-2958 **(6 pages)**.

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RESEARCH NOTE

Bacterial reduction in river water using nanocellulose membrane from pineapple biomass with ferrous-ferric oxide reinforcement

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ABSTRACT

BACKGROUND AND OBJECTIVES: Constructing a nanocellulose membrane from biomass waste can lessen harmful environmental effects owing to its ability to absorb chemical and microbiological impurities. Therefore, nanocellulose membranes with magnetic properties were developed as a powerful apparatus for reducing microbials and dyes in water.
METHODS: In this study, bacterial cellulose acetate-based nanocomposite membrane with ferrous-ferric oxide nanoparticle reinforcement was produced from pineapple peel biowaste extract through fermentation and esterification. High-pressure homogenization was used to produce nano properties of cellulose from pineapple. Meanwhile, the ultrasonic homogenizer was used to mix the produced nanocellulose with the ferrous-ferric oxide with various treatment (0.25, 0.50, 0.75, and 1.0 weight percent of cellulose acetate) to produce nanocomposite membrane. The membrane was then applied for the removal of bacteria and dyes. The samples were water from local rivers located near industries such as rubber, cement, and tofu industries. The effectiveness of the nanocomposite membrane at bacteria and dyes reduction was assessed.
FINDINGS: Nano cellulose membrane effectively reduced gram-negative bacteria and anionic dyes in the water samples. The ferrous-ferric oxide reinforcement enhanced the effectiveness of the membrane on bacteria and dye reduction. The addition of ferrous-ferric oxide resulted in a greater amount of dye degradation, and the presence of ≥0.75 percent ferrous-ferric oxide indicated an optimum ability to kill bacteria.
CONCLUSION: Ferrous-ferric oxide yielded good results in reducing the number of microbes and anionic dyes in the water samples tested. The results of this research can be used as basic data to advance the use of nanocellulose membranes as a biomaterial for controlling environmental impacts.

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44	5	0

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INTRODUCTION

Cellulose is a natural polymer that is important for the development of environmentally friendly products (Manuel *et al.,* 2020). Wood and other higher plants are the primary sources of cellulose. Algae, tunicates, and certain bacteria can also produce cellulose in relatively large quantities (Thomas *et al.*, 2020). Cellulose has been widely used on various scales, from macroscopic to nanoscale, to increase its function and usefulness. One application of nano-formed cellulose is a paper membrane that is generally used for eco-friendly water treatment technology. The recently developed membrane technology is becoming increasingly important (Deepa *et al.*, 2015). A significant breakthrough for the synthetic membrane industry began in the 1960s, although initial studies on membrane use started in the mid-18th century (Sofiah *et al.*, 2023; Zulaikha *et al.*, 2022, Patil *et al.*, 2021). The use of membranes for efficient ion separation from solutions has become a focus in the field of membrane science over the past few decades owing to the growing demand for more affordable technologies for wastewater treatment. Developing cellulose membranes from biomass waste is very promising because of its environmental impact. Biomass, a renewable organic material from plants and animals, provides a means to reduce waste contaminants through agricultural commodity-based industrial activities (Oliver Paul Nayagam and Prasanna, 2023; Samimi and Nouri, 2023). Such use of biomass is an effort to promote life cycle assessment (LCA) towards a greener environment (Rini *et al.,* 2021; Samimi, 2024). An example of this effort is the production of nanocellulose from pineapple peel waste. Owing to the large variety of aquatic waste in society, the cellulose nanomembrane produced from pineapple peel waste were given a strengthening treatment using ferrous-ferric oxide (Fe_3O_4). Fe_3O_4 has hydrophilic property (Azimi *et al.,* 2019); therefore, it facilitates the formation of intermolecular bonds between the oxygen in the Fe_3O_4 nanoparticles and hydroxyl groups of cellulose, which is reduced by the excess electrons provided by the hydroxyl groups. Another form of intermolecular bonding arises from electrostatic forces between the surface of Fe_3O_4 and cellulose fibrils. In addition, mechanical interlocking causes Fe_3O_4 to inhibit the movement of fibrils, thereby boosting the strength of the Fe_3O_4 nanocomposite system, which has proven effective in killing bacteria and destroying biofilms (Ma *et al*., 2022; El Sacker *et al*., 2021). The magnetic effect of metal oxide on waste water treatment has also been studied (Bellebcir *et al*., 2023; Wu *et al*., 2023). Reinforcement using metal oxides, specifically magnetite, is known to enhance the adsorption of metals, textile dyes, organic materials, nitrogen, phosphorus and facilitate antibacterial activities (Akbar *et al*., 2023; Lu Dong *et al*., 2021; Uchechukwu *et al*., 2021). This study was conducted to investigate the effectiveness of nanofibrillated cellulose (NCF) reinforcement for reducing bacteria and water waste components such as dyes. Three types of waste in the Padang city area with various suspected pollution were treated with NCF in this study. The information obtained from this research will become basic data for developing widely applicable NCFs. The aim of the current study was to identify the effectiveness of adding Fe_3O_4 to nanocellulose membrane developed from pineapple peel waste for bacteria and dyes reduction. The obtained data can provide basic information on developing NCF for waste management system. The study was conducted in Malang City, East Java and Padang City West Sumatera, Indonesia. The laboratory analysis was conducted at Agricultural Product Technology laboratories, department of food and agricultural product technology, Andalas University, from May to October 2023.

MATERIAL AND METHODS

Materials

The pineapple waste was collected from Blitar Regency. Acetobacter xylinum, a cellulose-producing microbe, was provided by the Applied Tech laboratory at Malang Muhammadiyah University, Indonesia. The characteristic of pineapple waste was described in the previous report (Suryanto *et al*., 2019). The chemicals were purchased form Smart-Lab, Indonesia, and the Fe_3O_4 was imported from Guangzhou Hongwu Co., China. The chemical used were in the pro-analysis grade.

Fabrication of bacterial cellulose

The process for generating nanocellulose membranes can be simplified into four steps:

1. Production of bacterial cellulose through fermentation
2. Nanofibrillation of cellulose

3. Formation of composite of a nanocellulose acetate membrane

4. Addition of metal oxide (Fe_3O_4) to strengthen membrane characteristics

Bacterial cellulose production

The bacterial cellulose was produced in adherence to predetermined procedures described in previous publication (Yanuhar *et al*., 2022). A mixture of 0.5 litre (L) pineapple peel extract, five grams (g) of glucose, and 2.5 g of ammonia acid were used to create the fermentation medium. Acetic acid (CH_3COOH) solution was added to the medium to maintain the potential of hydrogen (pH) level at 4.5. One hundred millilitres (mL) of Acetobacter xylinum was added to the medium to trigger the fermentation process. Static fermentation took place at a temperature between 25 degrees Celsius (°C) and 30°C. Bacterial cellulose then floated on the media, and were collected after 10 days and rinsed with aquadest to achieve a pH level of 7.0.

Bacterial cellulose fibrillation

The bacterial cellulose was fibrillated using the methods described by (Yanuhar *et al*., 2022). The pellicles underwent a pre-treatment phase that entailed exposure to a six percent sodium hydroxide (NaOH) alkali solution for two hours at 90°C prior to extraction. The cleaned pellicles were rinsed and divided into smaller pieces. Three hundred grams of these cleaned pellicles were treated in a crushing machine (ICHDS7 type, Fomac, China) at 25,000 revolution per minute (rpm) for five minutes after being soaked in 250 mL of distilled water. The final bacterial cellulose slurry was combined with 750 mL of distilled water before being put through a high-pressure homogenizer (Berkley-Scientific, AH-100D type, China). To collect the fibrillated bacterial cellulose slurry, a filtration procedure was used after the bacterial cellulose was fibrillated under a pressure of 150 bar.

Synthesis of cellulose acetate

In a beaker, 50 mL of glacial acetic acid was introduced into 2.50 g of bacterial nanocellulose. The mixture was stirred for thirty minutes. It was then stirred for another twenty-five minutes, while 0.32 mL of sulphuric acid (H_2SO_4) solution and 18 mL of CH_3COOH solution were added. The mixture was then filtered, following which 64 mL of anhydrous acetate was added. Thirty minutes of stirring followed. The solution was vacuum filtered after being laid aside for fourteen hours. The resulting precipitates were then oven-dried for a day at 70°C (Kirin, KBO-190RA) after being washed with aquadest until they were neutral (Cobo *et al*., 2017).

Reinforcement nanocomposite membrane production

A set of recognized procedures were followed for the fabrication of the cellulose acetate (Homem *et al*., 2020). Fifty millilitres of CH_3COOH and 2.5 g of fibrillated bacterial cellulose were combined in a glass beaker. The mixture was stirred for thirty minutes at room temperature. Subsequently, 0.32 mL of H_2SO_4 and 18 mL of CH_3COOH were added to the solution, which was then agitated for twenty-five minutes. Following filtration, 64 mL of acetic anhydride was added to the filtrate, and the mixture was agitated for 30 minutes. The resulting solution was allowed to precipitate for fourteen hours before being neutralized via aquadest-rinsing. It was then suspended in 200 mL of aquadest, agitated for 30 minutes, and sonicated for additional 30 minutes at 20 kilohertz (kHz), 400 watts (ultrasonic homogenizer, UP.400S-type, Lawson Scientific, China). Fe_3O_4 were added to the dispersion and sonicated for thirty minutes during this procedure. The Fe_3O_4 addition was set as 0.25; 0.5; 0.75 and 1 g per 100 g cellulose acetate, where the solution with no Fe_3O_4 was named as control. As previously noted, the dispersion was continuously agitated for two hours to achieve a homogeneous suspension, after which the mixture was baked at 120°C for four hours. The homogenous mixture was then combined with cellulose acetate and ultrasonically homogenized for one hour. Subsequently, the finished product was poured into a mold and baked for 24 hours at 60°C to dry it out.

Fe_3O_4 reinforcement morphology observation

The nanocellulose membrane structure was analyzed using X-ray diffraction (XRD) (PanAnalytical-Expert Pro, USA). The membrane was cut into 20 x 20 square millimetre (mm^2), then put in an XRD instrument. Analysis was conducted at a diffraction angle in the range of 10°-70°. For the analysis, CuKα were used as X-ray source with a wavelength of 1.542Å at 40 kilovolt (kV) and 30 mA (Suryanto *et al*., 2023). At a 25.0 kV acceleration voltage, the scanning electron microscope (SEM) (Inspect S50, Japan) was used to analyze the surface morphology. A coater (Emitech, SC7.620, United Kingdom) was used to apply a 10 nanometer (nm) layer of gold coating to the membrane prior to SEM inspection (Xiao *et al.*, 2015).

Bacterial determination in tested water

Three types of water samples were used in this study. The samples were collected from rivers that flowed around three industries, namely the cement, rubber and tofu industries. The NCF membrane was dipped in the water for ten minutes. Bacteria in water were grown on plate count agar and Luria agar to determine the effect of membrane contact on the membrane's bactericidal action. The viability of bacteria on the NCF membrane was also measured (Thammawong *et al*., 2019; Ding *et al*., 2023).

Pigment decolorization

The ability of the membrane to reduce azo dye components (rhodamine and acid orange) was investigated. Each pigment was made with a concentration of 50 part per million (ppm) and the membrane was dipped in each solution. The absorbance of the pigment solution was measured according to each specific wavelength using a spectrophotometer (Shimadzu-1800, Japan) before and after membrane immersion. All the experiments were repeated, at least, three times. The data were then processed statistically using Microsoft Excel (Fiana *et al*., 2023; Rini *et al*., 2023).

Statistical analysis

Statistical analysis was performed using the SPSS package program version 11.5 (SPSS Inc., Chicago, IL, USA). After the data were analyzed using one-way analysis of variance, the Duncan's multiple range posthoc test was run. The results were expressed using the triple samples' mean ± SD. $P<0.05$ was used to denote differences of importance (Samimi *et al.*, 2023).

RESULT AND DISCUSSION

The characteristics of the NCF nanocomposite were identified through XRD analysis (Fig. 1a). These patterns made it possible to identify the membrane's phase and crystal structures. Three major peaks were visible in membrane control, with values of 14.2°, 16.6°, and 22.5°, which correspond to the crystalline planes of [110], [100], and [200], in that order (Lee et *al*., 2015). The peaks in question represent natural cellulose (cellulose Iβ). Ferrous-ferric oxide nanoparticles were present in the nanocellulose membrane at peaks of 29.9°, 35.4°, 57.1°, and 62.6°. As the concentration of ferrous-ferric oxide nanoparticles increased, the strong diffraction peaks in the 10°–75° range showed increasing intensity. Owing to their surface growth on the membrane, the ferrous-ferric oxide nanoparticles seemed relatively weak within the nanocellulose membrane, which made it difficult to obtain the cellulose diffraction data during XRD testing. However, more ferrous-ferric oxide nanoparticles led to more self-agglomerated nanoparticles, which produced a more noticeable crystalline structure. The membranes' crystalline index was roughly 54.3 percent (%). The addition of 0.25, 0.50, 0.75, and 1.0 weight percent of ferrous-ferric oxide nanoparticles yielded crystalline indices of approximately 49.2%, 51.1%, 59.4%, and 68.3%, respectively. The membrane's crystalline index decreased with the addition of 0.25 wt% and 0.5 wt% ferrous-ferric oxide nanoparticles. The crystalline region of the cellulose membrane appeared to have been disrupted by the modest amount of ferrous-ferric oxide nanoparticles (Kaco *et al*., 2017); yet, the crystalline index value increased when the ferrous-ferric oxide nanoparticle content was increased to 0.75 wt% and 1.0 wt%. According to some researchers, the addition of magnetic nanoparticles can enhance the mechanical strength, thermal stability, optical transparency, electrical conductivity, and magnetic response of cellulose nanomaterials by enhancing the interactions between the materials (Evans *et al*., 2023). It can also increase the crystallinity of cellulose nanocrystals (Babaei-Ghazvini *et al*., 2020). It is conceivable that at the right concentration, ferrous-ferric oxide nanoparticles have a stabilizing effect that promotes the creation of crystalline areas, hence enhancing the crystalline structure of the nanocellulose.

The characteristics of the NCF nanocomposite was also identified through SEM analysis (Fig. 1b). It was inferred from the results that the Fe_3O_4 nanoparticle successfully integrated with the nanocellulose membrane formed from the pineapple peel. In this study, it was found that the membrane porosity was suboptimal. It was observed that the pores were not

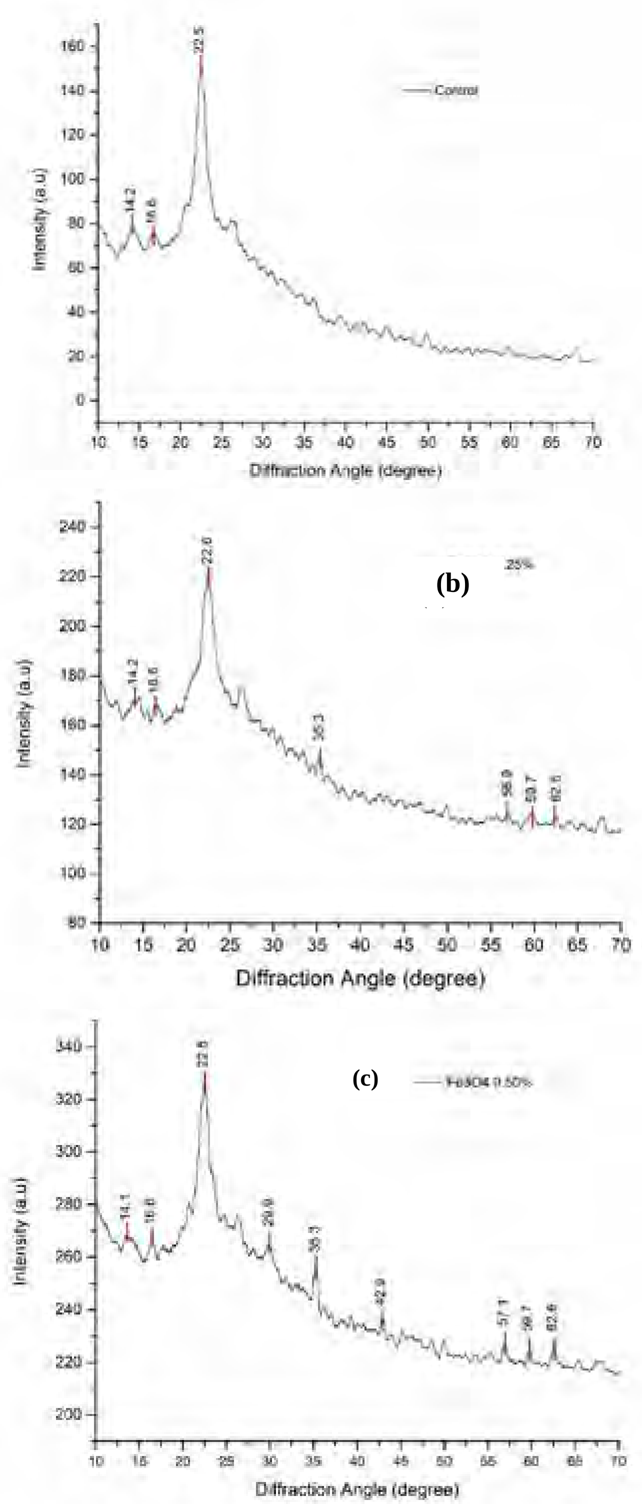
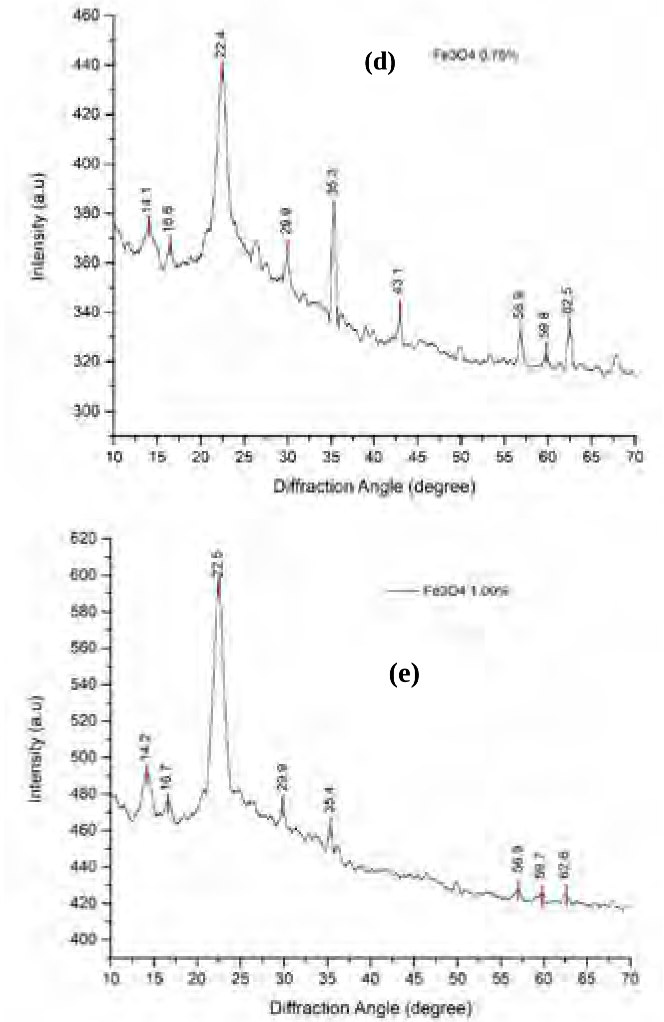


Fig. 1a: Diffractogram of nanocellulose membrane: (a) Control; (b) Fe_3O_4 0.25 wt%; (c) Fe_3O_4 0.5 wt%; (d) Fe_3O_4 0.75 wt%; (e) Fe_3O_4 1.0 wt%.

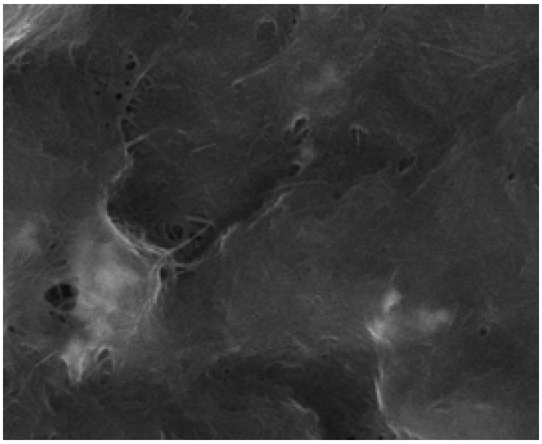


Continued Fig. 1a: Diffractogram of nanocellulose membrane: (a) Control; (b) Fe_3O_4 0.25 wt%; (c) Fe_3O_4 0.5 wt%; (d) Fe_3O_4 0.75 wt%; (e) Fe_3O_4 1.0 wt%.

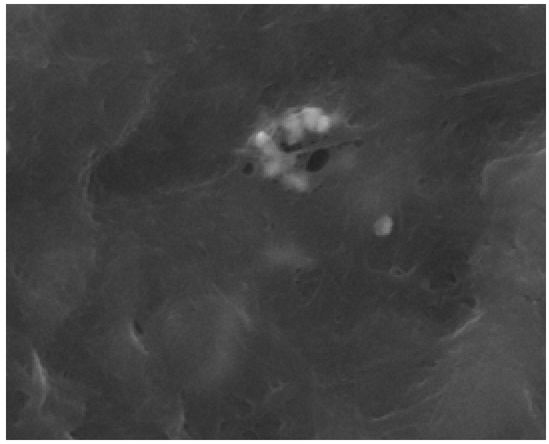
evenly distributed throughout the cell membranes. Moreover, the Fe_3O_4 treatments also blocked the pores. Therefore, the SEM information was crucial because it provided a starting point for establishing an approach to utilizing the membranes as a material for minimizing bacteria in water samples. However, membrane could not be used for water filtration because its porosity was suboptimal; therefore, the membrane immersion procedure was examined.

The immersion technique was superior to filtration for determining how effectively membranes decimated aquatic microorganisms. Compared to the filtering process, this technique required less effort. Previous researchers have demonstrated how challenging it is to combine nanocellulose combined with metal oxide composites in filtration materials (Ding *et al.,* 2023). A technique for submerging the membrane in a water sample is depicted schematically in Fig. 2. In this study, the number of bacteria that could be absorbed by the membrane and the likelihood of the bacteria surviving were used to determine how effectively bacteria in water might be reduced.

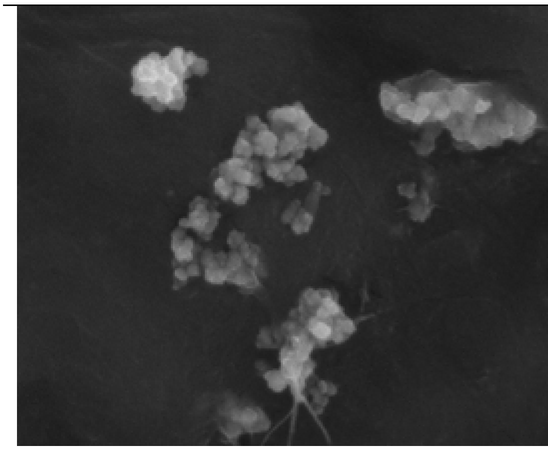
Figure 3 shows the number of bacteria absorbed by the membrane after immersion. The plate count agar media and Luria agar provide information



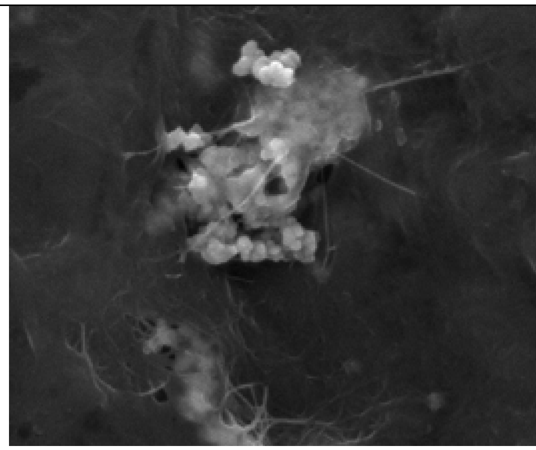
(a): SEM picture of NCF without Fe_3O_4 treatment



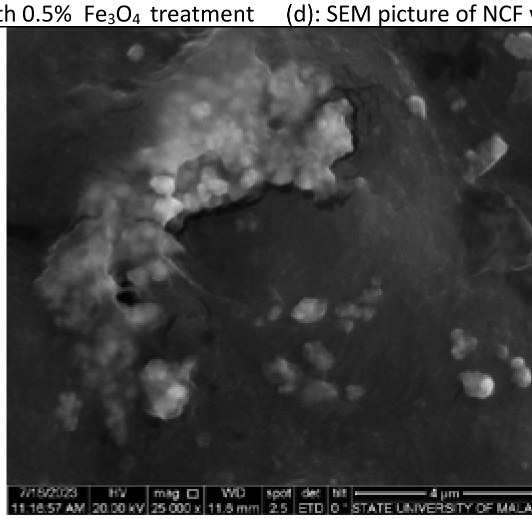
(b): SEM picture of NCF with 0.25% Fe_3O_4 treatment



(C): SEM picture of NCF with 0.5% Fe_3O_4 treatment



(d): SEM picture of NCF with 0.75% Fe_3O_4 treatment



(e): SEM picture of NCF with 1% Fe_3O_4 treatment

Fig. 1b: SEM picture of NCF with zero (a), 0.25% (b), 0.5% (c), 0.75% (d) and 1% Fe_3O_4 treatment

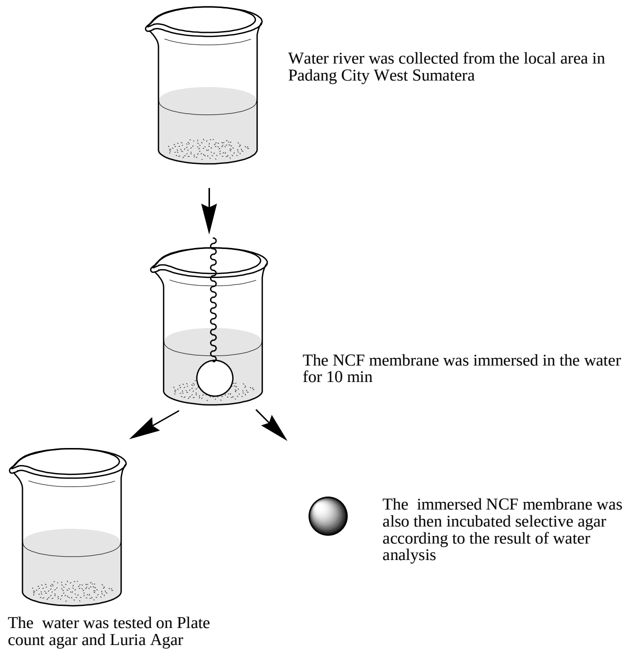


Fig. 2: Schematic work for observation of the nanocomposite membrane for bacterial removal in water sample

regarding the types of gram-positive bacteria (3a) and gram-negative bacteria (enterobacteria) (3b), respectively. Overall, nanocellulose from pineapple peel effectively absorbed the microbial content in the three types of water samples tested. A reduction of up to 50% of the initial bacterial content in the water samples for the two types of bacteria observed occurred. The use of Fe_3O_4 metal also had a positive effect on the resistance of bacteria present in the sample. The NCF membrane was more effective for gram-negative bacteria than for gram-positive bacteria. The response to the bacterial adsorption process also depended on the type of river water. For water samples from the rivers near the cement and rubber industries, the presence of Fe_3O_4 in the membrane at a concentration of 0.75% did not have a significant effect. In the tofu water samples, membranes treated with Fe_3O_4 gradually decimated both types of bacteria. Two types of mechanisms related to the bacterial reduction process can be proposed from the resulting data (Onyszko *et al.*, 2022; Sivansankari *et al.*, 2019). First, the ability of cellulose to absorb bacterial particles because of the interaction between the hydrogen bonds in cellulose and the bacteria, which makes the bacteria to bond with the cellulose molecules. Meanwhile, the presence of a metal component (Fe_3O_4), a positively charged component, produces an ionic cross-link with bacterial molecules. The influence of the charge was crucial in this phenomenon, where positively charged metals tend to form good bonds with negative charges. The situation might improve the way that NCF interacts with gram-negative bacteria. The surroundings of rivers can have an impact on the polluting elements found in their water. Therefore, different kinds of river water were used in this study. The river water in the vicinity of the cement factory has a comparatively alkaline pH and significant concentrations of insoluble particles. The water in the vicinity of the tofu and rubber industries are somewhat acidic. In addition, the profile of microorganism contamination fluctuates, with companies using organic raw materials typically experiencing higher levels of microbe contamination owing to the overall microbial content (Rini *et al.*, 2021).

For further analysis, the effect of Fe_3O_4 on the membranes' ability to kill bacteria was described. Figure 4 shows the viability of gram-negative bacteria that survived on the NCF membranes. The likelihood of bacteria adhered to the membrane surviving is demonstrated by these data. These data are

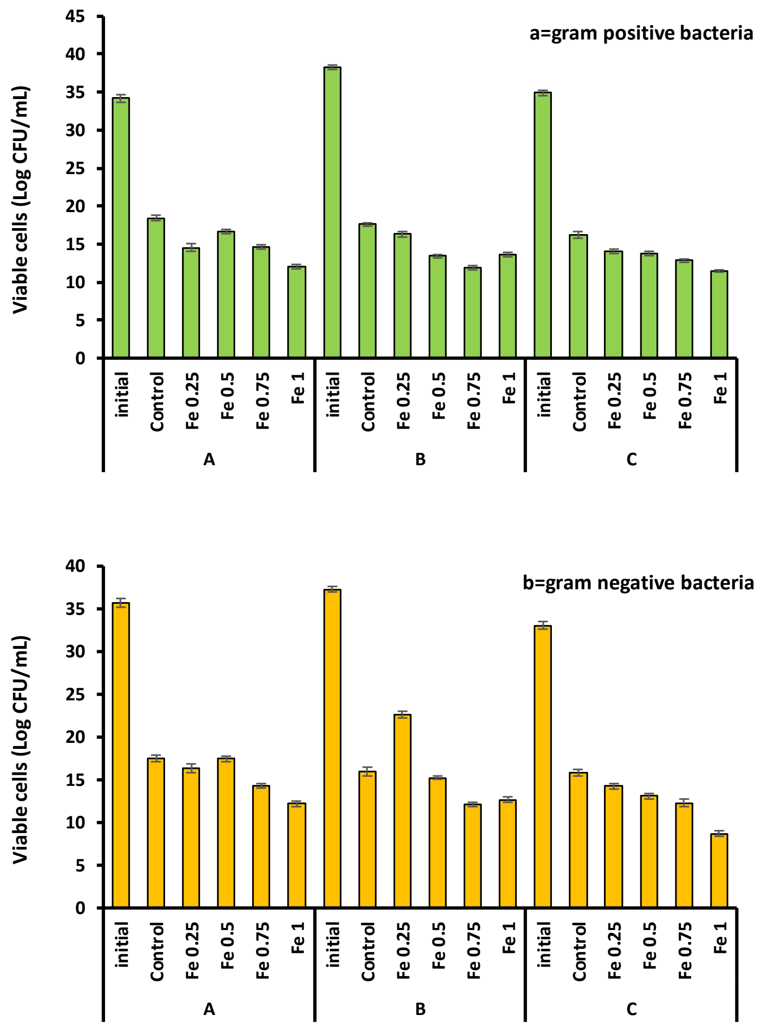


Fig. 3: Bacterial binding activity on the NCF membrane after immersion (a: gram-positive bacteria; b gram-negative bacteria; A: water river located near cement industry; B: water river located near from rubber industry; C: water river located near tofu industry)

essential because bacteria adhere to membranes following the membrane soaking process. Naturally, it is undesirable if bacteria exhibit strong membrane resistance because of the possibility of cross-contamination. The data show that the higher the concentration of Fe_3O_4, the lower the survival of bacteria. It was also found that using Fe_3O_4 concentrations between 0.25%-0.5% did not have a significant bactericidal effect because the bacterial viability value was the same as that of the control membrane. The Fe_3O_4 concentrations of 0.75% and 1% showed promising results for the viability value of bacteria that survived on the NCF membrane. The bacteria attached to the membrane died owing to the intense interaction between metal charges and hydrogen bonds in cellulose (Gudkov *et al*., 2021; Hernsdorf *et al*., 2017). This condition might be attributable to the damage to the protein cell walls of bacteria arising from the metal charge coating the NFC membrane (Janićijević *et al*., 2022; Muthukumar *et al*., 2017; Liu *et al*., 2021). It is recommended that future research be conducted to establish whether increasing the concentration of Fe_3O_4 would provide a better viability effect or trigger saturation. Bacteria experienced a decrease in viability of up to 26% after incubation on the membrane. Bacteria viability can

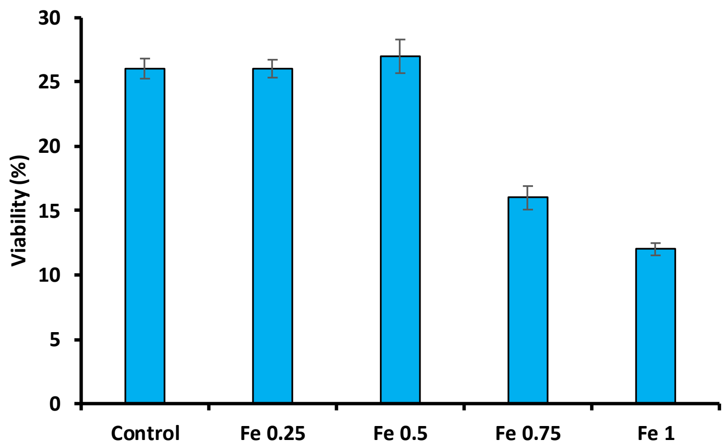


Fig. 4: Bacterial viability on the membrane NCF after incubation

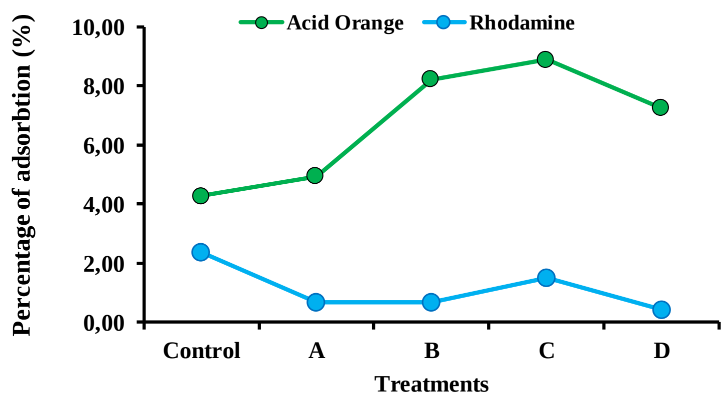


Fig. 5: Percentage absorption of pigments on the membrane NCF after immersion in treated water

be reduced up to 12%–26% by adding magnetite. The addition of magnetite concentration increases the membrane's ability to reduce the ability of bacteria to survive. Magnetite, such as Fe_3O_4, is known to have antimicrobial properties and can reduce the viability of bacteria, such as *Pseudomonas aeruginosa*, at the addition of 250 µg/ml. Metal ions can bind to mecapto, amino, and carboxyl groups in proteins (including enzymes) causing total or partial inhibition. Iron oxide ions can also damage the function and integrity of bacterial cell walls. It is known that magnetite tends to concentrate more on the outer and inner membrane surfaces of gram-negative bacteria, thus exhibiting stronger antibacterial capabilities. The results of this research show that magnetite is more effective at killing bacteria (bactericidal) attached to the membrane rather than limiting their growth (bacteriostatic).

The NCF membrane's capability to reduce the amount of azo pigment in water has also been measured, as additional research data in this study. Azo pigments or dyes can alternatively be categorized as cationic or anionic pigments (Oukebdane *et al*., 2022; Samimi and Safari, 2022; Vučurović *et al*., 2014). The pigment solution was simulated using 50-ppm pigment concentration in water. According to the proposed hypothesis, NCF membranes had a better adsorption effect on anionic pigment (Acid Red) than on cationic pigment (Rhodamine). The trend was significantly different. This information highlights the effectiveness of NFC membranes at reducing a component of water pollution, if it had a negative ionization charge. The river water samples contained both bacteria and domestic waste that were composed of both organic and inorganic components (Samimi and Shahriari Moghadam, 2020). Therefore, different rates of binding were observed for the various materials to the surface of the NFC, with those that had been enhanced with magnetite binding better. It is well known that magnetite possesses strong adsorption properties against metals, organic compounds, textile colors, nitrogen, phosphorus, and microorganisms (Lu Dong *et al*., 2021).

CONCLUSION

In this research, a bacterial nanocellulose membrane was developed. The membrane was produced from agricultural waste, specifically, pineapple peel. The active component from pineapple peel was changed enzymatically to produce cellulose fibers, which were then reduced to nano size and given magnetic properties with Fe_3O_4. The nanocomposite membrane that was fabricated from bacterial nanocellulose from pineapple peel with Fe_3O_4 reinforcement effectively removed bacteria and synthetic pigment in water. The Fe_3O_4 reinforcement of the nanocellulose membrane indicated a better result of material with a negative charge such as gram-negative bacterial and anionic pigment. The adsorption properties of nanocellulose coupled with the magnetic ability of Fe_3O_4 had a significant effect on reducing gram-negative bacteria and anionic pigments in water media. This research revealed that the adsorption quality of cellulose molecules can be increased by strengthening cellulose with the magnetic properties of Fe_3O_4. Cellulose is a polysaccharide biopolymer that is widely used as an adsorbent. However, the existence of strong intramolecular and intermolecular hydrogen bonds makes it difficult for cellulose to bond with other compounds. Adsorption was possible because cellulose, which initially has the negative properties of hydroxyl, also has a positive charge because it is coated in metal. This combination of positive and negative charges ultimately made the membrane performance better than when no treatment was applied. Therefore, cellulose must be combined with other materials to enhance its adsorption. The same trend was observed in membrane applications for dyes and bacteria with negative charges. Quite different results were obtained when the membrane was applied to remove positively charged dyes and bacteria. The similar charge as the magnetic properties of Fe_3O_4 made the membrane adsorption capacity inconsistent. Further research is required to clarify these findings. NCF with Fe_3O_4 made from pineapple peel can be further improved for more extensive communal water sanitation purposes. It is necessary to examine the distribution of Fe_3O_4 because, in this study, some of the membrane pores were covered owing to Fe_3O_4 treatment, such that the membrane could only be applied by immersion. Using a filtration system may provide better economic value in actual application. The use of filtration techniques will make it possible to treat a larger population while not overusing the membrane. In addition, the use of different metals as magnetic infrastructure should be considered to create more powerful NCF membranes. Further research is necessary to determine whether further contamination result from the use of NFC. Although there are no chances of cellulose contamination, it is important to ascertain that the membrane will not release Fe_3O_4 into water bodies. The potential use of pineapple waste to support mitigation of environmental problems will facilitate cleaner production in the pineapple industry so for LCA optimization.

AUTHOR CONTRIBUTIONS

D. Syukri has written the manuscript as well as concepted the research, H. Suryanto has contributed in reviewed the research concept and nanocellulose fabrication, F. Kurniawan was responsible for pigment reduction analysis, P.D. Hari has contributed for data processing, R.M. Fiana was responsible for fermentation process, R. Rini participated for the water sampling process.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percent
°C	Degree Celsius
µg	Micro gram
BNC	Bacterial nano cellulose
CH_3COOH	Acetic acid
Fe_3O_4	Ferrous-ferric oxide
H_2SO4	Sulphuric acid
kHz	Kilohertz
kV	Kilovolt
L	Litre
mA	Miliampere
mL	Millilitre
mm	Milimetre
mm^2	Square millimetre
Nm	Nanometre
NaOH	Sodium Hydroxide
NCF	Nano cellulose reinforcement
pH	Potential of hydrogen
ppm	Part per million
rpm	Revolution per minute
SEM	Scanning electron microscope
XRD	X-ray Diffraction

REFERENCES

Azimi, N.; Azimi, P.; Samimi, M.; Mansouri Jalilian, T., (2019). Ultrasonic-assisted adsorption of Ni (II) ions from aqueous solution onto Fe_3O_4 nanoparticles. Adv. Nanochem., 1(2): 66-72 **(7 pages).**

Akbar, K.I.; Rutuja, S. R.; Nitin, R. H.; Ashok, S. K,; Bapusaheb, H. S; Shashikant, P. P.; Satish, B. S.; Shaukatali, N. I., (2023). A review on environmental applications of metal oxide nanoparticles through waste water treatment, Materials Today: Proceedings. 2214-7853 **(10 pages)**.

Babaei-Ghazvini, A.; Cudmore, B,; Dunlop, M.J,; Acharya, B,; Bissessur, R,; Ahmed, M,; Whelan, W.M.,(2020). Effect of magnetic field alignment of cellulose nanocrystals in starch nanocomposites: Physicochemical and mechanical properties. Carbohydr Polym. 1; 247: 116688. **(10 pages).**

Bharali, P.; Bashir, Y.; Ray, A.; Dutta, N,; Mudoi, P,; Alemtoshi, S. V,; Vishwakarma, V,; Debnath. P,; Konwar B.K., (2022). Bioprospecting of indigenous biosurfactant-producing oleophilic bacteria for green remediation: an eco-sustainable approach for the management of petroleum contaminated soil. 3 Biotech. 12(1):13 **(19 pages)**.

Cobo, F.N.; Faria-Tisher, P.C.S.; Duarte, J.L.; Carvalho, G.M., (2017). Preparation and characterization of microporous cellulose acetate films using breath figure method by spin coating technique. Cellulose. 24: 4981–4995 **(15 pages).**

Deepa, B.; Abraham, E.; Cordeiro, N.; Mozetic, M.; Mathew, A.P., Oksman, K.; Faria, M.; Sabu Thomas, S.; Pothan, L.A., (2015). Utilization of various lignocellulosic biomass for the production of nanocellulose: A comparative study. Cellulose. 22: 1075–1090 **(16 pages).**

Ding, M.; Du, L.; Guo, A.; Qin, B.; Zhang, X.; Wu, K.; Wang, X.; Cai, A., (2023). A novel Fe_3O_4/CuOx nanozyme: Intrinsic peroxidase-like activity to kill bacteria and sterilize wounds. Appl. Surf. Sci., 625: 157185 **(14 pages)**.

Evans, S.K.; Wesley, O.N.; Koech, L.; Nelana, S.M.; Rutto, H.L., (2023). Structural Features of Cellulose and Cellulose Nanocrystals via In Situ Incorporation of Magnetic Iron Oxide Nanoparticles: Modification and Characterization. Coatings, 13, 39 **(15 pages).**

Elsacker, E.; Vandelook, S.; Damsin, G.; Van Wylick, A.; Peeters, E.; De Laet, L., (2021). Mechanical characteristics of bacterial cellulose-reinforced mycelium composite materials. Fungal Biol. Biotechnol., 8: 1–14 **(14 pages)**.

Fiana R, M.; Murtius, W.S.; Syukri, D.; Saskiawan, I., (2023). Azo Congo Red Dye Decolorization by Oyster Mushroom (Pleurotus ostreatus) F209. Asian J. Plant Sci., 22: 452-457 **(7 pages).**

Gudkov, S. V.; Burmistrov, D.E.; Serov, D.A; Rebezov, M.B; Semenova, A.A.; Lisitsyn, A.B., (2021). Do Iron Oxide Nanoparticles Have Significant Antibacterial Properties? Antibiotics (Basel)., 10(7): 884 **(23 pages).**

Hernsdorf, A.; Amano, Y.; Miyakawa, K.; Ise, K.; Suzuki, Y.; Anantharaman, K.; Probst, A.; Burstein, D.; Thomas, B.C.; Banfield, J.F., (2017). Potential for microbial H_2 and metal transformations associated with novel bacteria and archaea in deep terrestrial subsurface sediments. ISME J., 11: 1915–1929. **(15 pages)**.

Homem, C., Natália, Amorim, M.T., (2020). Synthesis of cellulose acetate using as raw material textile wastes. Materialstoday: Proceedings. 31: 2 **(3 pages)**.

Janićijević, A.; Pavlović, V.P.; Kovačević, D.; Perić, M.; Vlahović, B.; Pavlović, V.B.; Filipović, S., (2022). Structural Characterization of Nanocellulose/Fe_3O_4 Hybrid Nanomaterials. Polymers. 14: 1819 **(13 pages)**.

Kaco, H.; Baharin, K.W.; Zakaria, S.; Chia, C.H.; Jaafar, S.N.S.; Gan, S.Y.; Sajab, M.S., (2017). Preparation and characterization of Fe_3O_4/regenerated cellulose membrane. Sains Malays 46, 623–628. **(6 pages)**.

Lee, C.M.; Gu, J.; Kafle, K.; Catchmark, J.; Kim, S.H., (2015). Cellulose produced by Gluconacetobacter xylinus strains ATCC 53524 and ATCC 23768: Pellicle formation, post-synthesis aggregation and fiber density. Carbohydr Polym 133, 270–276. **(7 pages).**

Liu, L.; Chang, S.; Wang, Y.; Zhao, H.; Wang, S.; Zheng, C.; Ding, Y.; Ren, S.; Zhang, J.; Guo, Y.R., (2021). Facile fabrication of ion imprinted Fe_3O_4/carboxymethyl cellulose magnetic biosorbent: removal and recovery properties for trivalent La ions. RSC Adv., 21: 11(41): 25258-25265 **(8 pages)**.

Lu Dong, Z.; Mengqi Li, Y. Z.; Chen, Y.; Qi, y.; Wu, H., (2021). Organics and nutrient removal from swine wastewater by constructed wetlands using ceramsite and magnetite as substrates. Journal of Environmental Chemical Engineering, 9(1). 104739. **(9 pages).**

Ma, X.; Shi, Y; Liu, J.; Li, X.; Cui, X., Tan, S.; Zhao, J.; Wang, B., (2022). Hydrogen-Bond Network Promotes Water Splitting on the TiO_2 Surface. J. Am. Chem. Soc., 144: 13565–13573 **(9 pages)**.

Manuel, R.; Idrus, R.; Fauzi M.B., (2020). Plant- vs. bacterial-derived cellulose for wound healing: A Review. Int. J. Environ. Res. Public Health. 17(18): 6803 **(25 pages)**.

Muthukumar, H.; Chandrasekaran, H.i.; Mohammed, S.N.; Pichiah, S.; Manickam. M., (2017). Iron oxide nanomaterial: Physicochemical traits and in vitro antibacterial propensity against multidrug resistant bacteria. J. Ind. Eng. Chem., 45: 121-130 **(10 pages)**.

Oliver Paul Nayagam, J.; Prasanna, K., (2023). Response surface methodology and adaptive neuro-fuzzy inference system for adsorption of reactive orange 16 by hydrochar. Global J. Environ. Sci. Manage, 9(3): 373-388 **(16 pages).**

Onyszko, M.; Markowska-Szczupak, A.; Rakoczy, R.; Paszkiewicz, O.; Janusz, J.; Gorgon-Kuza, A.; Wenelska, K.; Mijowska, E., (2022). The cellulose fibers functionalized with starlike zinc oxide nanoparticles with boosted antibacterial performance for hygienic products. Sci. Rep., 12: 1321 **(13 pages)**.

Oukebdane, K.; Necer, I.L.; Didi, M.A., (2022). Binary comparative study adsorption of anionic and cationic azo-dyes on Fe_3O_4-bentonite magnetic nanocomposite: Kinetics, equilibrium, mechanism and thermodynamic study. Silicon. 14: 9555–9568. **(14 pages)**.

Patil, T.V.; Patel, D.K.; Dutta, S.D.; Ganguly, K; Santra, T.S.; Lim, K.T., (2021). Nanocellulose, a versatile platform: From the delivery of active molecules to tissue engineering applications. Bioact. Mater., 27(9): 566-589 **(24 pages)**.

Rini, B.; Anwar, K.; Teguh, T.K.; Daimon, S., (2021). Production of wood varnish from ambalau resin of *Durio zibethinus* (Murr.): A Preliminary Study. Asian J. Plant Sci., 20: 116-121 **(6 pages).**

Rini; Suryanto, H.; Hari, D.P.; Syukri, D.; Jaswandi, Kurniawan, F.; Makky, M., (2023). Application of Nanocellulose Biofilter from Pineapple Peel Waste for Water Microbes Removal. J. Environ. Public Health. 1-6 **(6 pages)**.

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Samimi, M.; Safari, M., (2022). TMU-24 (Zn-based MOF) as an advance and recyclable adsorbent for the efficient removal of eosin B: Characterization, equilibrium, and thermodynamic studies. Environ. Prog. Sustain. Energy, 41(5): e13859 **(9 pages).**

Samimi, M.; Shahriari Moghadam, M., (2020). Phenol biodegradation by bacterial strain O-CH1 isolated from seashore. Global J. Environ. Sci. Manage., 6(1): 109-118 **(10 pages).**

Sivasankari, S.; Kalaivizhi, R.; Gowriboy, N., (2019). Cellulose Acetate (CA) Membrane tailored with Fe_3O_4@ZnO Core Shell Nanoparticles: Fabrication, Structural analysis, and Its Adsorption Analysis. ChemistrySelect., 6: 2350–2359 **(10 pages)**.

Sofiah, A.G.N.; Pasupuleti, J.; Samykano, M.; Kadirgama, K.; Koh, S.P.; Tiong, S.K.; Pandey, A.K.; Yaw, C.T.; Natarajan, S.K., (2023). Harnessing nature's ingenuity: A comprehensive exploration of nanocellulose from production to cutting-edge applications in engineering and sciences. Polymers, 15: 3044 **(42 pages)**.

Suryanto, H.; Muhajir, M.; Sutrisno, T.; Mudjiono, Zakia, N.; Yanuhar, U., (2019). The Mechanical Strength and Morphology of Bacterial Cellulose Films: The Effect of NaOH Concentration. IOP Conference Series: Materials Science and Engineering, 515: 012053 **(8 pages).**

Suryanto, H.; Kurniawan, F.; Syukri, D.; Binoj, J.S.; Hari, P.D.; Yanuhar, U. (2023). Properties of bacterial cellulose acetate nanocomposite with TiO2 nanoparticle and graphene reinforcement, International Journal of Biological Macromolecules, 235 **(10 Pages).**

Thammawong, M.; Kasai, E.; Syukri, D.; Nakano, K., (2019). Effect of a low oxygen storage condition on betacyanin and vitamin C retention in red amaranth leaves. Sci. Horti., 246: 765-768 **(4 pages)**.

Uchechukwu, S. Ezealigo.; Blessing, N. E,; Samson, O. A.; Fabian, I. E., (2021). Iron oxide nanoparticles in biological systems: Antibacterial and toxicology perspective, JCIS Open, 4: 100027 **(13 pages).**

Vučurović, V.; Razmovski, R.; Miljić, U.; Puškaš, V., (2014). Removal of cationic and anionic azo dyes from aqueous solutions by adsorption on maize stem tissue. J. Taiwan Institute Chem. Eng., 45(4): 1700-1708 **(9 pages)**.

Thomas, P.; Duolikun, T.; Rumjit, N.P.; Moosavi. S.; Lai, W.; Johan. M.R.; Fen, L.B,. (2020). Comprehensive review on nanocellulose: Recent developments, challenges and future prospects. J Mech Behav Biomed Mater, 110:103884 **(21 pages).**

Wu, Y.; Liu, Y.; Kamyab, H.; Rajasimman, M.; Rajamohan, N.; Ngo, G.H.; Xia, C., (2023). Physico-chemical and biological remediation techniques for the elimination of endocrine-disrupting hazardous chemicals. Environ Res, 1: 232:116363 **(9 pages).**

Xiao, Y.T.; Chin, W.L.; Abd Hamid, S.B., (2015). Facile Preparation of Highly Crystalline Nanocellulose by Using Ionic Liquid. Adv. Mat. Res., 1087: 106–110 **(5 pages)**.

Yanuhar, U.; Suryanto, H.; Sardjono, S.A.; Ningrum, I.k.; Aminnudin, A.; Binoj, J.S., (2022). Effect of Titanium Dioxide Nanoparticle on Properties of Nanocomposite Membrane Made of Bacterial Cellulose. J. Nat. Fibers. 19: 13914–13927 **(24 pages)**.

Zulaikha, W.; Hassan, M.; Ismail, Z., (2022). Recent development of natural fiber for nanocellulose extraction and application. Materialstoday: Proceedings, 2265-2273 **(9 pages).**

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Podcasts

CASE STUDY

Economic feasibility, perception of farmers, and environmental sustainability index of sorghum-eucalyptus agroforestry

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ABSTRACT

BACKGROUND AND OBJECTIVES: The Indonesian Government is promoting sorghum as an alternative commodity to substitute wheat. The cultivation of this commodity on dryland is initiated in forestry areas through social programs. This study aimed to analyze the economic feasibility, perception of farmers, and environmental sustainability of sorghum-eucalyptus agroforestry in Majalengka.
METHODS: This study innovatively combined qualitative and quantitative methods to assess economic, social, and environmental aspects across five dimensions, namely business organization, actors, working mechanisms, economic impacts, and sustainability of business and environment. Data were collected through focus group discussions and interviews with questionnaires, containing 5 dimensions and 23 attributes. The data collected were analyzed using the revenue-cost ratio, Likert scale, and scoring formulation, as well as multi-dimensional scale method. The level of environmental sustainability status and leverage attributes were examined using the Rapfish program and Monte Carlo analysis.
FINDINGS: Sorghum-eucalyptus agroforestry was economically feasible with a revenue-cost ratio value higher than one. Farmers' perceptions regarding the five dimensions of sorghum-eucalyptus were positive except for the operational mechanisms, and business and environmental sustainability. A distinfuished area of unfavorable perception was the use of sorghum waste as a substrate for renewable energy. The environmental sustainability index for sorghum-eucalyptus agroforestry was categorized as low except for the economic (61.9) and actor (52.3) which attained the moderately sustainable. The results showed that the sustainability analysis using multi-dimensional scale could be used as a guide in formulating strategies for enhancing and developing sorghum-eucalyptus agroforestry in the future.
CONCLUSION: The problems in this study were related to the institutional governance of agroforestry business. The inclusion of the community, government, and private sector was unequal in carrying out the sustainability function of each dimension. The challenge for the future was proper and sustainable management of development efforts to realize economic sustainability, add value for society, and ensure environmental sustainability in agroforestry areas.

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INTRODUCTION

The Russian-Ukrainian conflict is endangering food security by disrupting wheat production and restricting exports to several developing countries (Mottaleb *et al.,* 2022), such as Indonesia. The demand for wheat is 11.17 million tons, while export restrictions have decreased the contribution from Ukraine between 2.83 million (2021) to 166 thousand tons (2022) (Indonesia of Statistics, 2023). The Indonesian Government has turned to sorghum as a wheat substitute. Given the comparable physical and chemical properties, sorghum flour serves as an effective substitute (Osibanjo *et al.,* 2022). Even though the flour cannot completely replace wheat, its use can be reduced. Biscuits using 30 percent (%) sorghum flour were proven to be acceptable in terms of quality and taste (Al Majzoub *et al.,* 2023) and 10% of the flour could produce bread with similar quality to that of wheat (Sibanda *et al.*, 2015). Using 60% or lower amounts can replace the use of wheat flour and improve the quality of noodles to become cheaper (Akajiaku *et al.,* 2017). Sorghum could also be used as livestock feed and a source of energy (Dube and Maphosa, 2022; Malherbe *et al.,* 2023). Incorporating this commodity into wheat flour mixtures offers a potential reduction in imports for developing nations (Adeyeye, 2016). The Indonesian government has preferentially enhanced the production and distribution of sorghum to increase income and ensure national food security. The 2024 roadmap for the development sets ambitious goals, namely a target cultivation area of 30,000 and 40,000 hectares (ha) with a yield of 115,848 and 154,464 tons by 2023 and 2024, spread across 17 provinces (Kemenkoekonomi, 2022). Sorghum is a drought-tolerant plant capable of adapting to dryland soil with scarce water availability and inferior soil conditions (Abdel-Ghany *et al.,* 202), and this commodity can also thrive in intercropping conditions (Ginwal *et al.,* 2021). Indonesia has the potential for dryland agriculture across 63.4 million hectares (Mha), including open-air grasslands and forested areas, but only 7.36 Mha are used for farming (Indonesia of Statistics, 2019). Assuming that sorghum is planted twice a year with an average yield of 6.75 tonnes per year, the potential for the production is 49.65 million tonnes of grain or the equivalent of 29.79 million tonnes of flour with a rendemen of 60%. The government has initiated the cultivation on dryland within forested areas through social forestry programs to improve land-use (Kemenkoekonomi, 2022). Land resource use must be rational and efficient to ensure both food and environmental sustainability (Ma and Chen, 2022). Implementing a sustainable land use management strategy is important. Agroforestry is a land-use system within forested areas that integrates agricultural and forestry practices. The aim extends beyond enhancing food profitability and sustainability to improve environmental functions, mitigate and adapt to climate change, improve biodiversity, and conserve land and water resources by ensuring sustainable landscape management (Octavia *et al.,* 2022). Agroforestry plays an important role in meeting socio-economic necessities (Sarveswaran *et al.*, 2023), and improving livelihoods of farmers through enhanced access to food, livestock feed, and timber (Akter *et al.*, 2022). It enhances greening, plant regeneration, water retention, and soil fertility (Ahmad *et al.*, 2021) to maintain environmental stability and strengthen resilience against climate change (Duffy *et al.*, 2021). Agroforestry is developed with a focus on ensuring sustained benefits and maintaining environmental integrity (Ahmad *et al.*, 2023), emphasizing diversity, and avoiding unfavorable side effects (Kaushal *et al.,* 2023). The concept is a sustainable land-use approach that enhances harvest yields by integrating crops with trees on the same plot (Divya *et al.,* 2022). This presents a more sustainable alternative to monoculture farming, offering greater benefits to farmers (Ramesh *et al.,* 2023). Ethiopian farmers practicing agroforestry report improved livelihoods compared to the counterparts (Wondimenh, 2023). The concept introduces diversity, increasing income, and employment opportunities in Uttar Pradesh, India (Kaushal *et al.,* 2023). Specific practices in Jaunpur District include block plantations, horticulture, silviculture, and scattered trees, predominantly eucalyptus (Kumar *et al.,* 2023). Eucalyptus-based agroforestry has proven more profitable than teak-based systems, and the plantations offer a broader open ground area (Widiyanto *et al.,* 2022; Samimi, 2024). Sorghum, a staple in Rajaf County-South Sudan, is extensively cultivated in agroforestry systems (Mayele and Bongo, 2022). The intercropping of this commodity in Taungya agroforestry in Sudan significantly increases income and productivity of farmers (Hemida *et al.,* 2023). Sorghum-based agroforestry in Indonesia started in Majalengka

District, West Java, with eucalyptus as the primary tree, on a land area of 30 ha. The initiation of the process was part of the government program and did not include all the community in Majalengka. The implementation yields varied social, economic, and environmental outcomes in and among different areas and countries. Comprehensive data regarding its socio-economic impact and sustainability remains limited. Agroforestry represents a participative process, including stakeholders from government, private sectors, and developmental business, contributing distinct production components and sharing in the profits (Dou *et al.,* 2023). The adoption of these multifunctional systems is dependent on socio-economic, agroecological, and environmental factors. Recognizing the variables that influence the adoption of these systems is crucial for shaping policy frameworks conducive to agroforestry practices (Awazi *et al.,* 2023). Stakeholders, including government and non-government entities, scientists, organizations, and farmers, play an important role in agroforestry advancement, and a united approach to foster its implementation at various administrative tiers (Divya *et al.,* 2022). This study focuses on discussing the economic feasibility, perception of farmers, and the environmental sustainability of sorghum farming using a eucalyptus-based agroforestry system in Majalengka. The hypotheses on the dimension of business organization, actors, and working mechanisms on the social side, are an important factor in achieving economic and environmental sustainability. This contributes to enriching the existing knowledge regarding agroforestry, community-based forest management (CBFM), and the ramifications on socio-economic and environmental sustainability. This current study is a reference for policy architects to analyze the feasibility, farmers' perception, and environmental sustainability index of sorghum-eucalyptus in Majalengka, Indonesia, in 2022.

MATERIALS AND METHODS

Description of study areas

Data collection was conducted for three months from October to December 2022 in Kertajati Sub-district, Majalengka District, Indonesia. Majalengka covers 1,204.24 square kilometers (km^2), making up 3.40% of West Java Province, and is segmented into three geographical zones, namely high, hills, and low plains with elevations between 19 to 857 meters (m) above sea level. This location harbors 20.263 ha of community and state forests and is renowned for producing a variety of agricultural commodities such as paddy, corn, sweet potatoes, cassava, mung beans, peanuts, and soybeans (Majalengka of Statistics, 2023). The land area is 18,177.63 ha (15.10% of Majalengka total administrative area) with the eucalyptus plantation covering 10,600.25 ha (58.32% of Majalengka agroforestry land area) entirely in Kertajati Sub-district (Perhutani, 2022). In the lowlands, Kertajati experiences maximal and minimal rainfall with 646 and 9 millimeters (mm) in November and September at coordinates 6°39'45.0" S and 108°05'29.0" E (Fig. 1) (Kertajati of Statistics, 2022). Sorghum, traditionally known in the locale as 'epoy', has been a staple in Majalengka, and the modern cultivation methods were integrated with innovative agricultural technology in forest areas starting in 2021. This cultivation occurs cooperatively with the State-owned Forestry Company (Perhutani) through a CBFM scheme in designated forest lands. Kertajati has evolved as a pivotal area for the development, using agroforestry systems in the community territories managed by the Forest Management Units (KPH) of Cibenda, Kertajati. Agroforestry, located in areas with flat topography, has developed as the main source of livelihood for the local population. The main crop planted on land is eucalyptus and the agricultural commodities cultivated are rice, corn, and sorghum. The cultivation pattern applied on agroforestry land is rice-sorghum-ratoon sorghum in the alleys between rows of eucalyptus. The cultivation of eucalyptus around sorghum can help prevent wild animals and birds from damaging or eating the plant due to the strong smell. Agroforestry with this commodity can also increase biodiversity as well as control pests and plant diseases. Sorghum is a well-suited companion for cultivation alongside eucalyptus trees within the context of agroforestry. This agricultural approach is adopted by farmers who possess forestry cooperation protection certificates (SK Kulin KK). These certificates symbolize a mutually beneficial and highly productive partnership between Perhutani and the local farming communities. The potential for sorghum and eucalyptus cultivation in Kertajati is 1,300 ha. Farmers with SK Kulin KK have the opportunity to plant sorghum in agroforestry areas, as part of the government program.

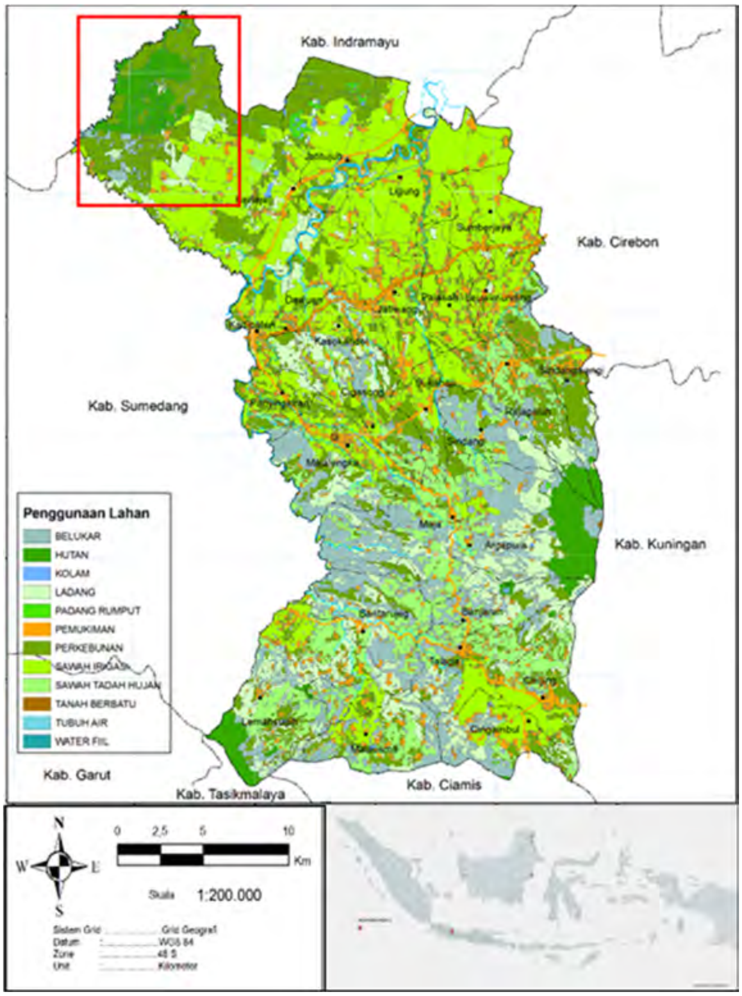

Fig. 1: Geographic location of agroforestry areas shown by red square, in Kertajati, Majalengka, Indonesia

Sampling methods

The study sample area was purposively selected, with Kertajati identified as a development site for sorghum in the eucalyptus agroforestry. They are 100 farmers with experience in cultivating the commodity in this agroforestry area and surroundings. These farmers, representing 100% of the cohort, were included as respondents in the census.

Data collections

Primary data were gathered qualitatively and quantitatively to provide a comprehensive overview and build a deep discussion of the results. Qualitative data produces new insights and theories into social and political actions, while quantitative data scientifically explains these concepts (Kang and Evans, 2020). Quantitative and qualitative data use measurable numerical information to explain and understand a situation (Zhou, 2022). Quantitative data collection was conducted with structured questionnaires and focused on collecting data through observations and census activities. Qualitative data collection was carried out through semi-structured indepth-inteview, and Focus Group Discussions (FGD). Participants in FGD included representatives from government, private sector, community leaders, Forest Village Community Institution (LMDH), Forest Farmer Groups (KTH), sorghum processing unit, and off-takers. The aim of FGD was to extract information concerning sorghum use in the eucalyptus agroforestry area and to verify the previously compiled dimensions and environmental sustainability attributes based on references. The sustainability approach combines social and ecological variables in an activity, process, or human product (Salaz-Zapata and Ortiz-Munoz, 2018). The concept shows social and economic aspects such as social interaction, and the various components (Cirella *et al*., 2020). The correlation between the social and economic aspects is the basis for the elaboration of dimensions and attributes for assessing environmental sustainability. Adopting agroforestry principles and practices will benefit farmers economically as well as society in a positive way (Dwivedi *et al*., 2023). FGD was followed by a census of farmers using a questionnaire directly against 100 respondents. The questions asked include the characteristic of respondents, the input production, output, price of input and output of sorghum farming, and the by-product. Other questions are related to perception of the community towards 5 dimensions and 23 attributes formulated during FGD, namely: i) organizational or institutional dimensions of business (4 attributes about the form, structure, rules and performance of organization), ii) stakeholder engagement (4 attributes related to government, private, public and gender involvement), iii) working mechanism (5 attributes related to capital, production input, technology, market, local wisdom), iv) economic impact (5 attributes related to income, employment absorption, market opportunities, secondary business opportunities, and auxiliary business opportunities), and v) business and environmental sustainability (5 attributes related to upstream-downstream sorghum business, business diversification, waste use for fertilizers, waste use for renewable energy, and forest conservation). The census was followed by semi-structured in-depth interviews and observations conducted to learn more about the development of sorghum in the agroforestry area and clarify some information difficult to retrieve from the questionnaire. In-depth interviews were conducted with key informants from governmental elements (village government, Department of Food Sustainability, Agriculture, and Fisheries District of Majalengka, Field Farmers), foresters, public figures, the head of LMDH, chairman or manager of KTH, farmers, processing group, and traders.

Data analysis

Characteristic of respondents

The characteristic of respondents includes gender, age, education, household size, experience with sorghum cultivation, the scale of the farm in the forest area, and income derived from sorghum farming. The data are represented in a table, showing criteria, ranges, percentages, and ratio values.

Economic feasibility of sorghum-eucalyptus agroforestry

Data on input production and output were calculated resulting in the average used. The costs are derived from the average and price of inputs. The revenue is derived from the cumulative value of the main and the by-product value of grains. The calculations for revenue and income adhere to the model proposed using Eq. 1 (Meena *et al*., 2023).

Gross income (GI) = Value of main product + Value of by-product

$$GI = Q_{mp} \times P_{mp} + Q_{bp} \times P_{bp} \quad (1)$$

Where:

GI = Gross income

Q_{mp} = Quantity of main product

P_{mp} = Price of main product

Q_{bp} = Quantity of by-product

P_{bp} = Price of by-product

The R/C is determined using Eq. 2 (Syuryawati *et al*., 2020).

$$\text{R/C ratio Analysis} = \frac{\sum_{i=1}^{m} Yi.Pyi}{\sum_{i=1} Xi.Pxi} n \quad (2)$$

Where:

∑ = Number from i to m or i to n

Yi = Production (kg/ha)

Pyi = Production price (USD/ha)

Xi = Cost of farming (USD/ha)

Pxi = Price of input (USD/ha)

i ... m = Number of productions obtained

i ... n = Number of inputs used

R/C >1 means that sorghum farming is efficient, because the revenue received is greater than the expenditure, R/C = 1 shows the break-even (income is equal to expenditure), and R/C <1 means sorghum farming is inefficient because revenue is less than expenditure.

Farmer’s perceptions regarding sorghum-eucalyptus agroforestry

Data on farmer's perceptions regarding sorghum development are ordinal and analyzed using a scoring method, according to Parnabhakti and Puspaningtyas (2021). This variable is evaluated using a Likert scale, ranging from 1 to 4, corresponding to the categories of 'very good', 'good', 'bad', and 'very bad'. Subsequently, the data are analyzed using a scoring formulation as Eq. 3 (Parnabhakti and Puspaningtyas, 2021).

$$\text{Score value} = (n\_i.s\_i)/N\_i \quad (3)$$

Where:

ni = The number of respondents in the i column (i = 1, 2 , 3)

si = Statement score in the-i (i = 1, 2, 3)

Ni = The number of respondents in the i row (i = 1, 2, 3)

Farmer's perceptions regarding sorghum development are categorized using a three-grade interval scale of high, medium, and low in Eq. 4 (Ratnawati and Vivianti, 2020).

$$\text{Interval scale} = (\text{maximum value} - \text{minimum value})/(\text{the number of interval scale}) \quad (4)$$

The perception performance of farmers regarding sorghum-eucalyptus agroforestry development is visualized in the form of a histogram.

Environmental sustainability index of sorghum-eucalyptus agroforestry

The environmental sustainability of sorghum-eucalyptus agroforestry development is evaluated using Multi-dimensional Scaling (MDS) method. Assessments from FGD participants concerning the sustainable development serve as the foundation for establishing the dimensions and attributes of each dimension. The confirmations are thoroughly analyzed and assessed in MDS analysis stages to identify the attributes in each dimension impacting the sustainability of business (Kavanagh and Pitcher, 2004). MDS uses the Rapfish (Rapid Appraisal of Fisheries) software, emphasizing multi-criteria analysis (MCA) principle and relying on the algorithm (Fauzi and Anna, 2022). The stages of sustainability include: i) Definition of attributes: attributes associated with the development of sorghum agroforestry are determined and adjusted based on field observations and literature studies. These are formulated during FGD and in-depth interviews with key informants, previous study references, as well as the adaptation to the situational context and conditions of the site. ii) Attribute scoring: each attribute in each dimension is assigned an ordinal score ranging from 0–10. This is based on scientific judgment, representing a spectrum from the lowest (0) to the highest (10) rating. A score of 0 and 10 signify poor and optimal contribution to sustainability. The higher value contributes to the sustainability of business. iii) Multi-dimensional analysis of scores: the score values are subjected to multi-dimensional analysis using the Rapfish program to ascertain sustainability status. Indices and sustainability statuses are categorized according to Kavanagh and Pitcher (2004), as outlined in Table 1.

iv) The evaluation of sustainability level: sustainability level of business is assessed by evaluating the index and status of each dimension, including the calculation of the value and visualizing the concept in a spider web diagram. MDS values are derived by averaging sustainability of each dimension. This evaluation shows the extent of the environmental sustainability of sorghum agroforestry business and analyzes areas in need of enhancement. v) Leverage analysis: this is used to analyze sensitive attributes identified based on priority sequences from the analysis results, examining the root mean square (RMS) ordination changes on the x-axis. A higher RMS value change signifies a substantial role or sensitivity

Table 1: The category of index and sustainability status

Index Value	Category
0.00 – 24.99	Unsustainable
25.00 – 49.99	Less sustainable
50.00 – 74.99	Moderately sustainable
75.00 – 100.00	Highly sustainable

of the attribute in improving continuity status to enable observation or amendment. vi) Monte Carlo Analysis: This analysis evaluates the error level in attribute score creation, variation, and the ordination process due to value differences, stability of MDS analysis process repetitions, data input errors or loss, and high-stress values of MDS analytics (Kavanagh and Pitcher, 2004). vii) Model validation: this includes examining the stress value, square correlation (SQR), and the disparity between the Monte Carlo value as well as the analysis results against the actual data. A stress value below 25% is deemed good, and SQR close to 100 shows optimal model performance. The discrepancy between the Monte Carlo value and the analysis results should not exceed 5% (Kavanagh and Pitcher, 2004). This validation determines the model adequacy in representing the acquired data.

RESULTS AND DISCUSSION

Characteristic of respondents

The survey respondents comprised 77% men and 23% women among the practitioners. The median age was 46.8 years, and 59% were categorized in the 41–60 age bracket, while 28% were under 40. A total of 77% had completed 6 years of schooling, 12% experienced between 7 to 9 years of education, and the remaining had more than 10 years. Farmers usually had families of 2–7 members, with 83% supporting 3–5 people. Sorghum was predominantly cultivated in and outside forest areas. A minor 2% of farmers had been growing this commodity for 2.1–3.0 years, and 98% had less than 2 years of experience. The land harvested in forest areas was 1.3 ha, where 71% and 12% cultivated sorghum on 0.50–1.00 ha and 1.51–2.00 ha. Incomes from farming varied, with an average of USD 493.08 per growing season. A total of 35% earned above USD 514.30, and 23% earned less than USD 385.72. Table 2 shows the characteristic of respondents at the study location.

Sorghum-eucalyptus agroforestry farming in Majalengka predominantly includes men and women, constituting 77.00% and 23.00%. This gender dichotomy implicates a larger socio-cultural context where traditional roles designate men as primary cultivators and decision-makers, affirming the findings of Ibrahim and Nabage (2023). The predominance

Table 2: The characteristic of respondents (Bank Indonesia, 2023)

Description	Criteria	Amount (%)	Average
Gender	Men	77 (77.00)	-
	Women	23 (23.00)	
Age (years)	<30	7 (7.00)	46.8
	31–40	21 (21.00)	
	41–50	38 (38.00)	
	51–60	21 (21.00)	
	>60	13 (13.00)	
Education (years)	<6	77 (77.00)	7.1
	7–9	12 (12.00)	
	10–12	8 (8.00)	
	>13	3 (3.00)	
The number of family dependents (person)	≤2	13 (13.00)	3.4
	3–5	83 (83.00)	
	>6	4 (4.00)	
Sorghum farming experiences (years)	≤1	25 (25.00)	1.7
	1.1–2	73 (73.00)	
	2.1–3	2 (2.00)	
Size of land cultivation (ha)	<0.50	3 (3.00)	1.3
	0.50 –1.00	71 (71.00)	
	1.10–1.50	8 (8.00)	
	1.51–2.00	12 (12.00)	
	>2.00	6 (6.00)	
Sorghum farming incomes (USD/season)	≤385.71	23 (23.00)	493.08
	392.15–450.01	19 (19.00)	
	456.44–514.30	23 (23.00)	
	>514.30	35 (35.00)	

Noted: Primary data, 2022 (processed): 1 USD = 15.555 exchange rate October 2022 allows men greater access to resources and a decisive role in the adoption of new technology (Aduwo *et al.,* 2017), reflecting the extent of socio-cultural norms and values (Ndubi *et al.,* 2023). The agricultural sector has experienced intensified gender campaigns since the 1990s (Chete, 2019), stating the equitable distribution of resources (Quisumbing *et al.,* 2014) and recognizing the substantial contributions of women in various agricultural activities (Chakma and Rubu, 2021). Gender differences in sorghum-eucalyptus agroforestry still exist despite the increasing inclusion of women in agribusiness organizations and management. The demographics of farmers are composed of individuals of productive age, including the millennial generation, a factor that has a positive implication for sorghum farming. Age and educational attainment significantly influence the receptivity to agroforestry technology (Wijayanto *et al.,* 2022). Farming experiences and farm size are also determining factors that influence the adoption of technology (Awe *et al.,* 2021). Young people seem more willing and interested in agriculture. This interest is seen as a hopeful sign for the future of agriculture (Hasan *et al*., 2022). A significant proportion of these farmers have limited educational backgrounds, impacting the understanding and adoption of innovative technology and modern agricultural method (Ghosh *et al.,* 2023). Education is important, influencing management levels and output (Ninh, 2021) as well as individuals' capability to make informed decisions as a catalyst for community empowerment and sustainable ecosystem preservation (Aziza *et al.,* 2023). The size of the household is an important factor affecting the implementation of agroforestry (Ibrahim and Nabage 2023), and influencing family income and welfare (Sulasni and Suwendra, 2021). This variable drives farmers to obtain diversified income sources, such as sorghum-eucalyptus agroforestry business to enhance livelihoods and fulfill family responsibilities. A significant correlation exists between farming experience, land area, and the adoption of agroforestry practices (Ngango *et al*., 2023). Most farmers in the area have relatively limited experience in sorghum business, impacting crop management and yield (Cock *et al.,* 2023). The land in forest areas is cultivated ranging from 0.5–2.0 ha for sorghum. The extent of cultivated land positively correlates with income (Akbar and Fawwaz, 2022), and necessitates higher farming costs related to production inputs and labor. Success in farming is not exclusively limited to the extent of land cultivated but depends on production efficiency (Lai *et al.,* 2018). The income derived from sorghum-eucalyptus agroforestry business in one cultivation season varies, ranging between USD 385.72 and USD 514.30. Farmers need to manage land efficiently and improve knowledge and skills in sustainable agricultural practices, as well as sorghum cultivation to raise income. Successful implementation of agroforestry to increase agricultural productivity and income depends on a better understanding of benefits, sufficient technical support, and use of agricultural land (Kamal *et al.,* 2023).

Economic feasibility of sorghum-eucalyptus agroforestry

Sorghum farming in eucalyptus agroforestry areas is economically viable with an R/C value of >1. Components of production cost, including fixed and variable cost, are analyzed to assess the economic feasibility. Fixed cost, comprising of the annual land rental value converted per cultivation season, amounts to USD 40.18/season as sorghum farming occurs in two distinct seasons, namely main cultivation and ratoon maintenance. Variable cost differs between the main plant and maintenance (ratoon), standing at USD 541.31 for the former and USD 300.55 for the latter, including production inputs and labor costs. The cost for the main crops consists of expenses for seeds, fertilizers, pesticides, and labor for various farm activities, from cultivation to harvesting and transport. The cost of ratoon maintenance covers fertilizers, pesticides, and labor for treatments, pest control, and harvesting. Sorghum yield includes grains and plant waste (stems and leaves), with the main crop yielding lower than ratoon, namely 3,000 kg/ha compared to 3,750 kg/ha, which is a 25% increase. The waste also experienced a 33.34% increase from the main crop to the ratoon. The price for both was USD 0.19/kg, and the total income from sorghum-eucalyptus agroforestry farming was USD 1,574.95, where 47.86% was derived from plant waste. Table 3 shows a comprehensive analysis of sorghum-eucalyptus agroforestry farming.

Farmers have the opportunity to carry out farming in the eucalyptus agroforestry area in groups through collaboration with Perhutani. Socio-economic benefits are obtained from land ownership permits for the

Table 3: Analysis of sorghum-eucalyptus agroforestry farming in Kertajati, Majalengka, Indonesia in 2022 (Bank Indonesia, 2023)

Description	Sorghum production	
	Main crops	Ratoon 1
Production cost		
Fixed cost	40.18	40.18
Variable costs	541.31	300.55
a. Production inputs (USD)	149.15	94.82
b. Labors (USD)	392.16	205.72
Total cost	581.49	340.73
Production		
Grain (kg)	3,000	3,750
Sorghum plant waste (kg)	22,767	30,357
Price (/kg)		
Grain	0.19	0.19
Sorghum plant waste	0.02	0.02
Revenue	1,090.87	1,406.30
Grain production	578.59	723.24
Sorghum plant waste	512.28	683.06
Income	509.38	1,065.57
R/C	1.9	4.1

Noted: Primary data, 2022 (processed): 1 USD = 15,555 exchange rate October 2022

production of seasonal crops. Incomes are earned from farming sorghum and other annual crops, but are required to analyze eucalyptus. Integration of the commodity with eucalyptus plantation is considered economically feasible based on input-output analysis for two harvest times, namely the main crop and ratoon maintenance. The income is obtained from the sale of grains and sorghum plants as food and animal feed. The proportion of labor costs incurred is greater than the production inputs. The cost incurred on the main plant is 72.45% and 68.45% of total production and ratoon maintenance. These are higher than the costs of sweet sorghum farming in Wuyuan, China and India at 63% (Liu *et al.,* 2015) and 40–54% of total production costs (Gautam *et al.,* 2021). High labor costs of sorghum-eucalyptus agroforestry farming in Majalengka economically have a positive impact on the absorption of agricultural labor. The average absorption is 80 men/day/season, with wages of USD 4.50 for 6–7 hours of work/day. The use of labor is comparable to agricultural production in India with an average of 84.64 men day/ha/season (Kumar *et al.,* 2017). The potential area for cultivation in Kertajati is 1300 ha with labor costs of USD 597.88/ha/year, resulting in the economic value from employment opportunities at USD 777,244/year. The income derived from the primary crop amounts to USD 1,090.87, with 53.04% and 46.96% attributed to grains and sorghum waste. The income generated from the ratoon is at USD 1,406.30, comprising 51.43% and 48.57% from grains and sorghum plant waste. Income obtained by farmers in Maros, South Sulawesi, from sorghum plant waste is between USD 446.03–603.72/ha (Syuryawati *et al.,* 2020). Sorghum-eucalyptus agroforestry in the main crop has an R/C value of 1.9 and 4.1 in ratoon maintenance. This shows the economic feasibility of the commodity through the main cropping pattern and ratoon maintenance. Agroforestry system in Sudan has been recognized to yield higher economic returns compared to monocropping (Fahmi *et al*., 2018). The farming of the commodity with ratoon maintenance enhances profitability by managing the costs of production inputs and labor (Sari *et al*., 2022). The production from ratoon, including grains and waste, surpasses the main crops, and offers better quality (Zhou *et al.,* 2022). Sorghum waste, used directly or through fermentation as animal feed, serves as a raw material for producing sugar, ethanol, wax, fiber, paper, and building materials (McCuistion *et al*., 2019). There is a substantial opportunity to increase the added value of sorghum through product diversification from both grains and waste.

Perception of farmers regarding sorghum-eucalyptus agroforestry

Perception of farmers regarding the prevailing business organization, such as LMDH, is positive, with scores ranging between 3.14–3.57, reflecting good to very good results for the future. Perception of stakeholder support and inclusion in sorghum-eucalyptus agroforestry efforts are also high, with scores falling between 3.27–3.88, indicating very good. Perception of farmers on the working mechanisms of LMDH are more varied between 1.29–3.14, showing a spectrum of views from challenging to easy to implement. Perception of the economic impact of sorghum-eucalyptus agroforestry business is favorable, with values between 2.43–3.27. Public views on business and environmental sustainability are diverse, spanning from poor to good. An area of unfavorable perception is the use of sorghum waste as a substrate for renewable energy. Fig. 2 shows the varied perception of farmers on sorghum-eucalyptus agroforestry.

Sorghum-eucalyptus agroforestry farming in Majalengka is a business considered new. The community perceptions regarding the development tend to express a future orientation in the present realities and the existing business organization, LMDH. This organization has evolved into an important entity, capable of providing farming input needs and alternative market options as well as establishing connections among the community, government, and capital providers. LMDH has not worked as expected, requiring comprehensive technical and institutional support to meet the community expectations. Most farmers in the low hills of Himachal Pradesh have a positive perception of agroforestry and can be promoted to practice the concept through improved extension services, cooperative groups, and distribution of quality cultivation materials and products (Pathania *et al*.,

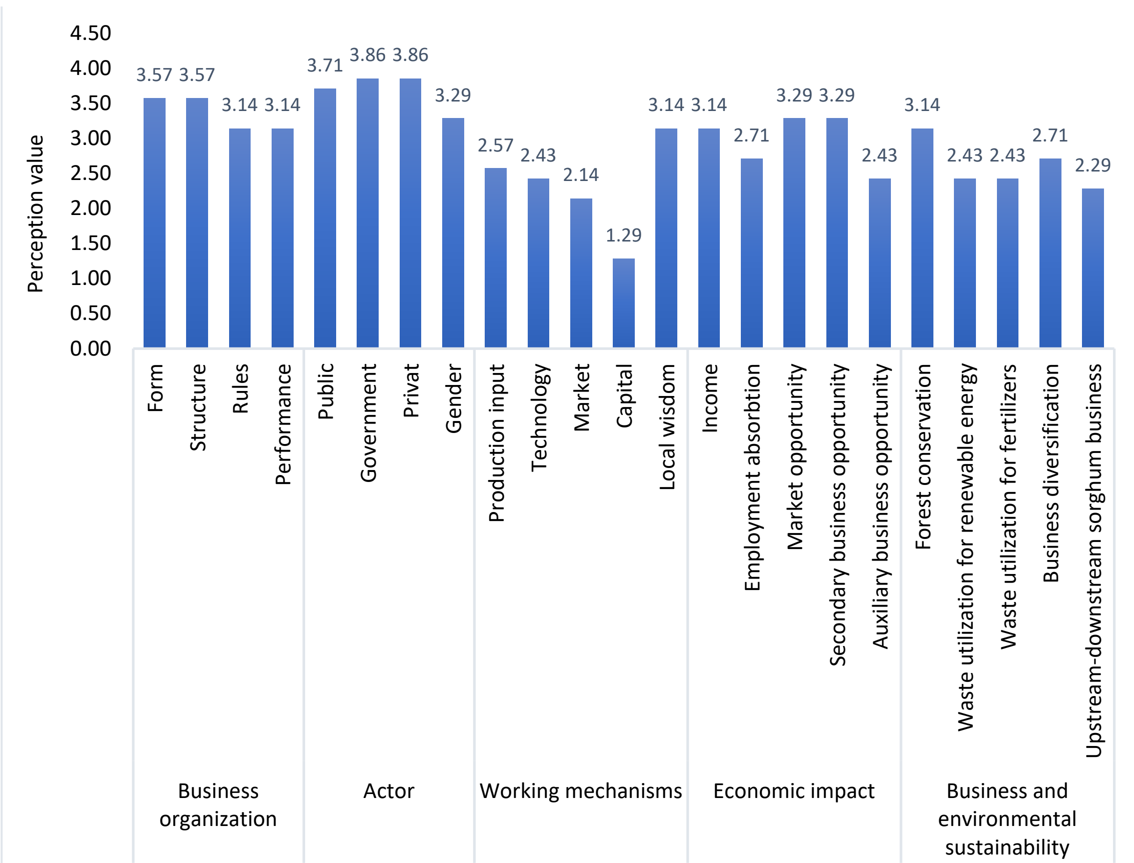

Fig. 2: Perception of farmers on the development of sorghum-eucalyptus agroforestry business in Kertajati, Majalengka, Indonesia, 2022

2020). The community stresses the indispensability of government and private sector, such as Perhutani support for sustaining the business and achieving successful land management in forest areas. The absence of support decreased the development of sorghum-eucalyptus agroforestry business. Farmers, constrained by limited resources, access to markets, and connectivity with external entities, heavily rely on support to overcome the limitations. The proactive inclusion of the government and corresponding entities is important in enabling small farmers to implement agroforestry for community livelihood sustainability in forest areas (McGunnigle *et al.,* 2023). Perception of farmers on agroforestry and decisions to implement are influenced by factors including social relationships, historical memory, practical abilities, and the existence of formal and informal institutions (Wienhold and Goulao, 2023). The government and other responsible entities must support and assist small in the implementation of agroforestry for the sustainability of community livelihoods in forest areas (Tega and Bojago, 2023). This is because agroforestry is a catalytic factor adopted through targeted programs, policies, and practices by the government and related agencies (Islam *et al.,* 2021). The community finds the operational mechanisms of the sorghum-eucalyptus agroforestry business ranging from manageable to challenging, with business capital being the most elusive aspect. There is also a collective desire for governmental intervention to facilitate access to business capital. Sorghum production technology is perceived as integrative with local wisdom, offering lucrative market opportunities due to the economic value of the plant and the by-products. Limited market access may affect government intervention to expand opportunities for sorghum and increase the diversity of the products. Poor market accessibility, lack of subsidies, and credit facilities are major problems faced in the low hills of Himachal Pradesh (Pathania *et al*.,2020) and the Indus River Basin, Pakistan (Mahmood and Zubair, 2020). The perceived economic ramifications of sorghum-eucalyptus agroforestry are positive, attributed to its potential to elevate income, generate employment, and create new business ventures. The community perceives the production as a catalyst for the creation of supportive business opportunities managed by the organization related to sorghum seeds, fertilizers, and other inputs. Sorghum production has the potential to increase income compared to other cereal crops (Chavula and Turyasingura, 2023). Preferences of farmers for design and commodity selection can increase the motivation to implement agroforestry system in the long term (San *et al*., 2023). The practices in Faridpur District of Bangladesh are considered to increase agricultural productivity and household income, as well as an effort to achieve food security (Saha *et al.,* 2018). The community expects that sorghum business can create other opportunities for the organization (LMDH) including the provision of farming inputs, sorghum seeds, and fertilizer. The community perception of sustainability is in the moderate sustainable category, such as in the attribute of land conservation activities. Sorghum-eucalyptus cultivation pattern does not have a negative impact on forest conservation efforts. This is because eucalyptus is planted in an alley system with a distance between rows of around 5–7 m, and the crown is small, allowing annual plants to grow optimally without interfering with each other. This is necessary to provide understanding among farmers regarding eucalyptus allelopathy (Ramesh *et al.,* 2023). The community has an unfavorable perception regarding the aspect of using sorghum plant waste as raw material for renewable energy, organic fertilizer, and diversification of food processing. This is understandable since the location is far from technological sources and there is minimal assistance from the government. Tokede *et al.,* (2020) recommend extension workers and other stakeholders to deliver knowledge about the practices and benefits of agroforestry to farmers in the simplest form for easy understanding. Positive perception of farmers on the five dimensions studied show that the business is quite promising because of the high economic value. Comprehensive support from the government and private sectors is very important, particularly for LMDH. The support should not be fragmentary but holistic, addressing the current deficiencies of the community in managing sorghum-eucalyptus agroforestry business. This facilitates access to technology, farming inputs, alternative markets, and capital. The benefits can be realized by creating supportive legislation, improving extension services, using the results of study and innovation (Shukla *et al.,* 2021), and increasing awareness regarding the enduring benefits of the system (Wondimenh, 2023).

Environmental sustainability indexes of sorghum-eucalyptus agroforestry

The analysis results show that the environmental sustainability index for sorghum-eucalyptus agroforestry business is low since the highest achieved values attain the 'moderately sustainable' category in the economic (61.9) and actor (52.3) dimensions. The index values for work mechanism (41.7) and business organization (42.8) fall into the 'less sustainable' category, and the business and environmental sustainability dimension is marked at 19.8 in the 'unsustainable' category. These results show the presence of numerous aspects and conditions in sorghum-eucalyptus agroforestry business. Fig. 3 shows a detailed representation of the environmental sustainability index across the five dimensions in sorghum-eucalyptus agroforestry business.

Dimensions of business organization

The index value in the organizational dimension shows that sustainability is relatively low. The organizational activities consistent with the memorandum of association/articles of association (AD/ART) are scored poorly. Attributes such as the establishment of a legal entity, the community inclusion in the structure, and adherence to AD/ART have received reasonably good scores (Fig. 4). In-depth interviews report that these scores accurately reflect the prevailing conditions in the field. The establishment of LMDH in Kertajati is supervised by a community representative and managed by the members. Since LMDH abides by AD/ART, the concept is recognized as a legal organization. The role has predominantly been as a mediator between Perhutani and KTH, coordinating the cultivation, maintaining, and harvesting of eucalyptus plants owned by Perhutani. LMDH as an enabling institution for CBFM, particularly those related to sorghum, remains unclear. The establishment formalizes the eucalyptus plant maintenance activities between Perhutani and the community.

Actor dimensions

The assessment of the actor dimension shows a relatively sustainable status, with an index value of 52.3. This moderate level of sustainability in the actor dimension can be attributed to less-than-optimal attributes in the level of community and private sector support as shown in Fig. 5. This observation is consistent with in-depth interviews, indicating the prevalent influence and leadership of Perhutani in determining community inclusion and support in land management in forest areas. The existing relationship is restricted to land ownership and tenancy, serving as labor for Perhutani and being compensated for

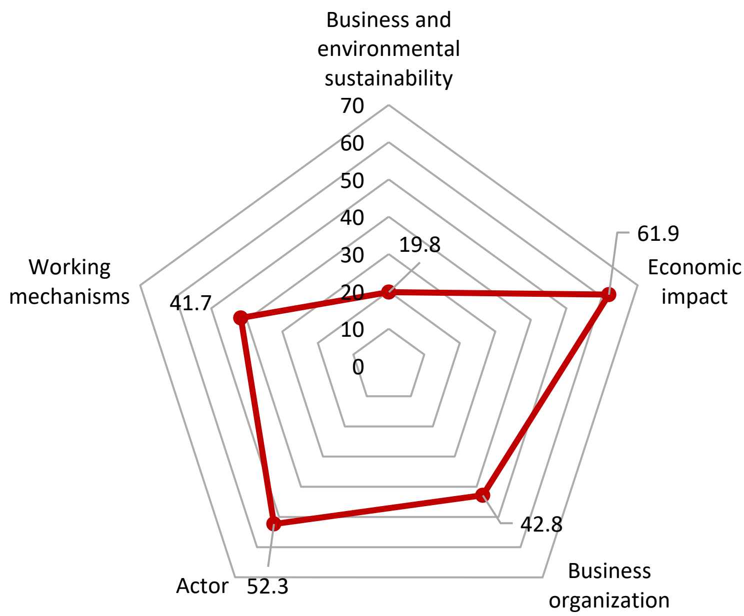

Fig. 3: Sorghum-eucalyptus agroforestry business environmental sustainability index

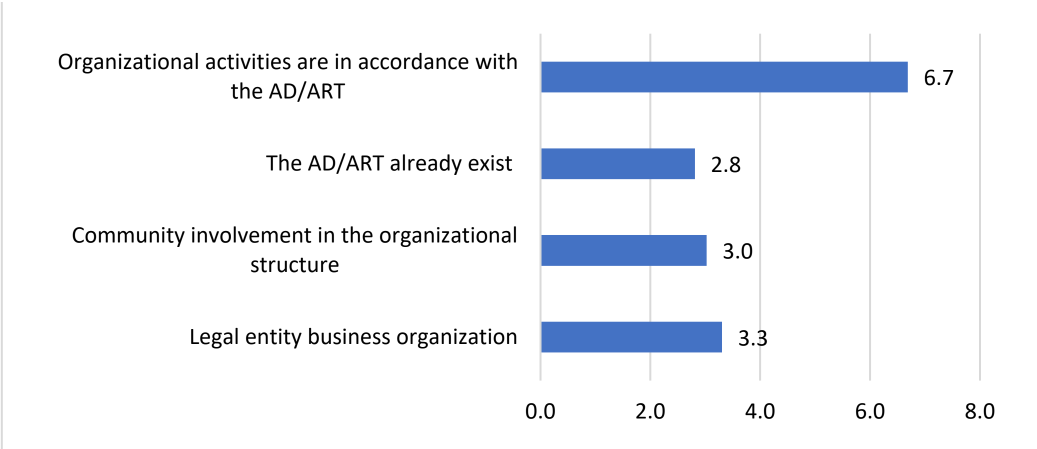

Fig. 4: Leverage of attributes in business organization dimensions

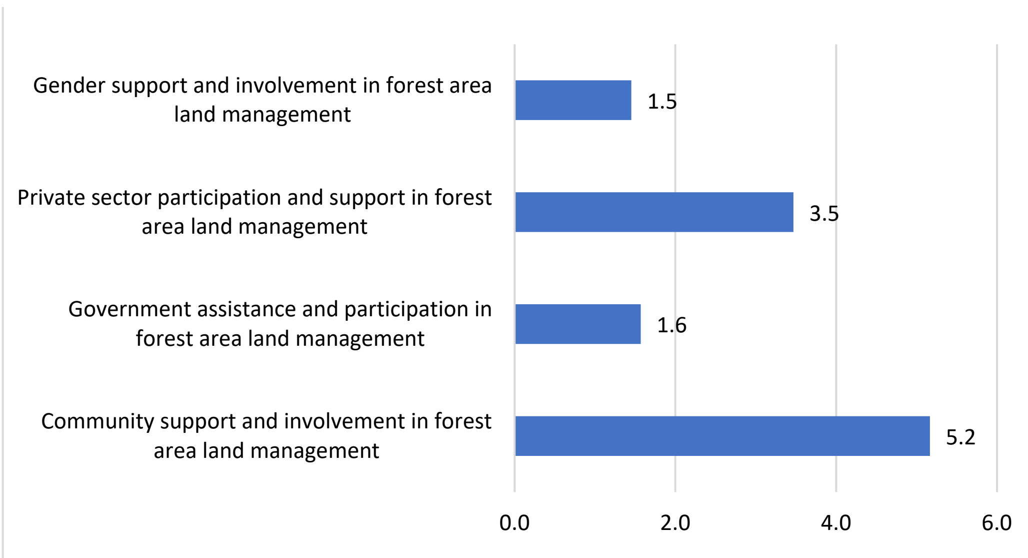

Fig. 5: Leverage attributes in the actor dimension

each related activity including eucalyptus. Therefore, the community essentially functions as an object for Perhutani's agenda. Furthermore, no additional private entities have shown any form of support or engagement in sorghum business. The community expects the inclusion of the private sector in providing farming inputs and acting as off-takers for sorghum, to ensure sustainability in the established commodities. Even though government support and inclusion are viewed positively and act as a propellant for the sustainability of the agroforestry venture, a deeper analysis shows a unilateral, top-down approach to governmental support. The government has not implemented a collaborative strategy in the planning stages with the community predominantly positioned as the recipient of the program.

Dimensions of working mechanisms

The evaluation of the working mechanism dimensions indicates a less sustainable. Three attributes positively contribute to the working mechanism dimensions of sorghum-eucalyptus agroforestry operation. The first factor is the production process which is streamlined seamlessly with existing local wisdom, eliminating potential conflicts. The efficient marketing and beneficial pricing of sorghum, as the second factor, are facilitated by lead farmers or local intermediaries. This is enhanced by the high sale prices driven by the current scarcity of sorghum during the rising demand. The challenge of securing business capital adversely affects the sustainability index of the working mechanism dimension as the third factor. Farmers benefited from the support in 2021 in the form of seeds, fertilizers, and pesticides to cultivate sorghum as a local agricultural service forestry area development program. The community encountered obstacles in the subsequent season because of sparse availability and elevated prices of high-quality sorghum seeds in the market, restricting the plantation of sorghum except for farmers with ample capital. Access to government-subsidized fertilizers is not universal due to quota limitations, leaving the majority struggling to acquire capital for the business without government assistance. This less sustainability in working mechanisms is connected to the actor dimension. The government treats the community as passive recipients rather than active and empowered contributors in sorghum business. Fig. 6 shows the leverage attributes in the working mechanism dimension.

Dimensions of economic impact

The results in the economic impact dimension show a state of moderate sustainability, achieving a value of 61.7. Interviews with farmers showed that the integration of sorghum and eucalyptus in agroforestry practices has the potential to enhance employment opportunities, broaden market access, and elevate income levels. Sorghum farming is considered unsuccessful in generating businesses that support production, such as those focused on producing sorghum seed or supplying farming inputs. The farming has not provided new business opportunities in the agroforestry areas, and the commodity only serves as an alternative source of income. There is an absence of businesses transforming sorghum into processed food items to potentially elevate the value-addition prospects. Fig. 7 shows the leverage attributes associated with economic impact.

Dimensions of business and environmental sustainability

The assessment results for the business and environmental sustainability dimensions fall into the 'unsustainable' category, representing the least

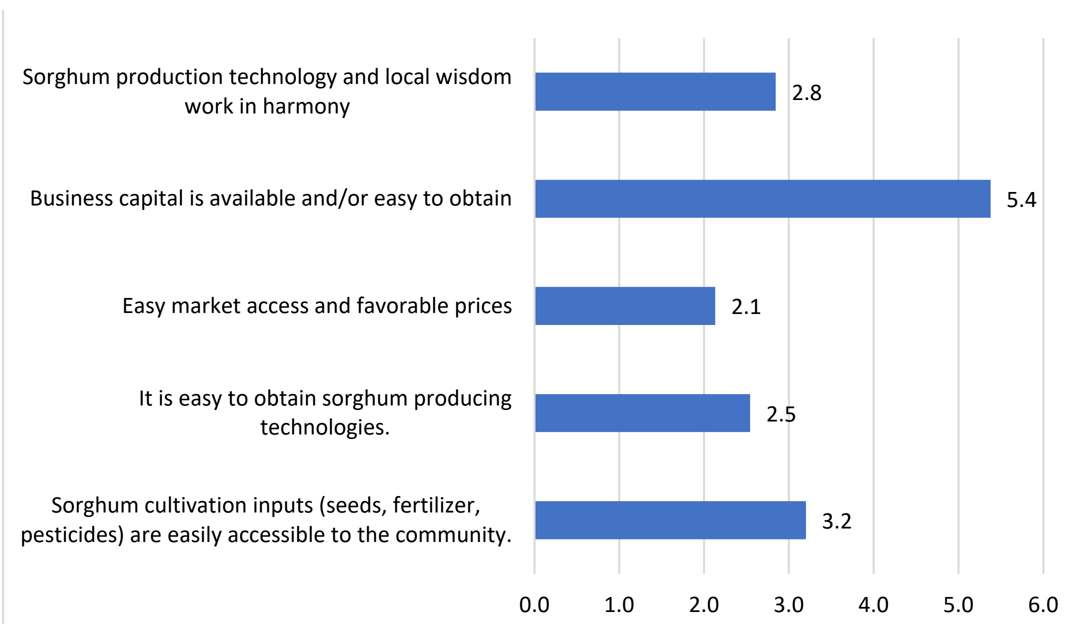

Fig. 6: Leverage attributes in the work mechanism dimension

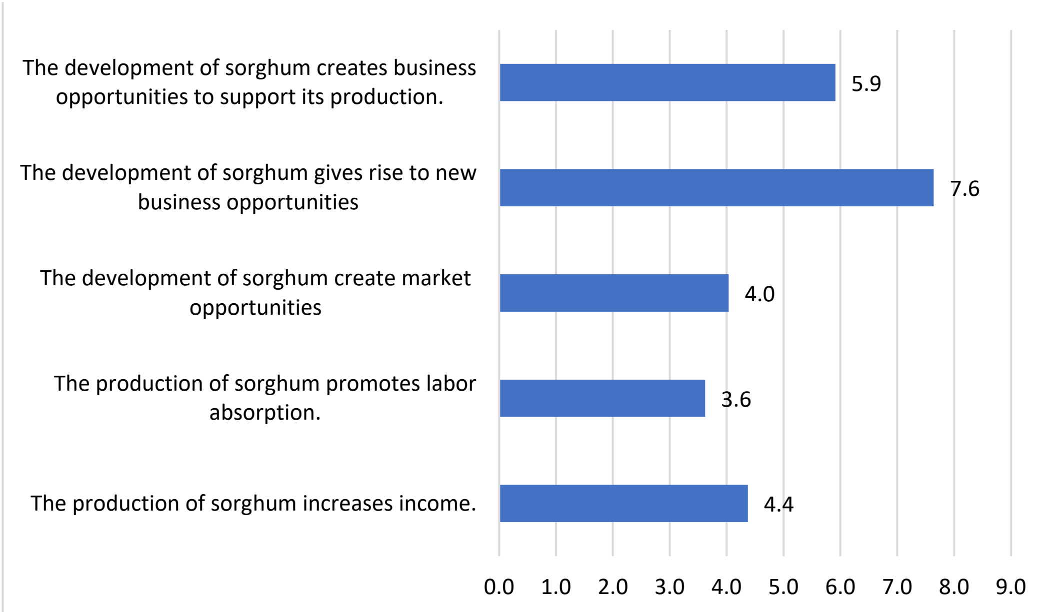

Fig. 7: Leverage attributes in the economic impact dimension

favorable outcomes compared to other dimensions. Three important attributes need attention to improve the dimension in sorghum-eucalyptus agroforestry practices. These include i) the absence of initiatives to leverage sorghum waste for organic fertilizer, ii) a lack of structured management for the development of products, from upstream to downstream, in the agroforestry landscape, and iii) the non-initiation of using sorghum waste for renewable energy. The efforts to convert sorghum waste into organic fertilizer are in an experimental phase, conducted by a limited number of farmers. Insights from in-depth interviews show that farmers have not been adequately informed concerning the potential economic value of processing sorghum waste into organic fertilizer and renewable energy sources. This waste is sold directly for animal feed, as a beneficial by-product of sorghum-eucalyptus agroforestry system. The situation correlates with the results from the business organization dimension, showing that the consistency of activities with AD/ART remains suboptimal. This is because LMDH activities are predominantly confined to mediating interactions between Perhutani and tenant farmers. Fig. 8 shows the leverage attributes within the business and environmental sustainability dimensions.

Validity of environmental sustainability index data analysis

The sustainability index for each dimension is presented in Table 4. The model used is considered appropriate with stress values ranging from 0.13 to 0.15, and an R^2 value of 0.95, showing appropriateness. The resulting environmental sustainability index has an average of 43.7 or less sustainable, but the data has been studied using a robust model, credible and accountable.

The environmental sustainability of sorghum-eucalyptus agroforestry business in Majalengka remains low, mainly due to the lack of support and collaborative partnership amongst local government, private sector entities such as Perhutani, and the community. Previous studies showed that community forests in Bogor, Indonesia, had moderate sustainability and required improvement through comprehensive stakeholder engagement (Sukwika *et al.,* 2016). Achieving higher indices necessitates more inclusive approaches from the government and private sectors, beyond top-down initiatives or strategies perceiving the community as beneficiaries. Future policies should state the environmental awareness of farmers, show the balance between ecological conservation and

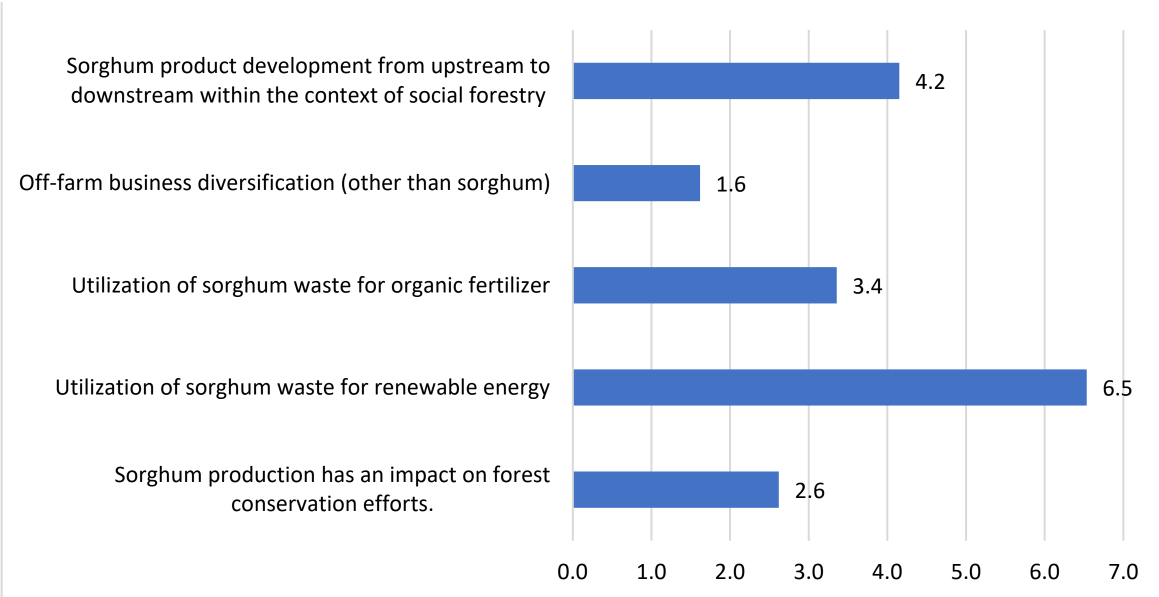

Fig. 8: Leverage attributes in the dimensions of business and environmental sustainability

Table 4: The sustainability index of five dimensions, and data quality indices

Dimensions	Index	Stress	R^2 (SQR)	Status
Business organization	42.8	0.1449	0.9559	Less sustainable
Actor	52.3	0.1504	0.9542	Moderately sustainable
Work mechanism	41.7	0.1305	0.9574	Less sustainable
Economy	61.9	0.1353	0.9500	Moderately sustainable
Continuity	19.8	0.1497	0.9525	Unsustainable
Average	43.7			Less sustainable

economic progression, as well as strengthen and sharpen farmers' way of thinking (Lei *et al.,* 2023). Success in sorghum-eucalyptus agroforestry depends on community participation across planning, rule establishment, and continuous program implementation. Collaborations with non-governmental entities and external bodies are important for the advancement of LMDH (Ramadhan *et al.,* 2022). Several attributes significantly influence the low environmental sustainability values in the dimensions, with distinct interrelations leading to decreased scores across different dimensions. The incongruence of business activities with the organization AD/ART contributes to the low value. The community expects that LMDH will become a business institution helping in sorghum cultivation activities, providing production facilities such as seeds and fertilizer, becoming a local off-taker, and finding buyers from outside the area to facilitate the marketing process. The community seeks the assistance of LMDH in facilitating the establishment of business capital institutions in proximity to forested areas due to the constraints posed by limited access to capital resources. The actor dimension's less sustainability is attributed to inadequate support and engagement from the government, the private sector, and the community in forest land management. Collaboration between actors and communities plays a role in ensuring the sustainable management of forests (Aisharyaa *et al.*, 2020). These two dimensions show no relationship between Perhutani and the community, as the landowner and tenants. Effective CBFM, reliant on community support, is crucial for enduring sustainability (Hajjar *et al*., 2021). The inclusion in agroforestry program needs to be supported by the government and other entities (Tega and Bojago, 2023). The concept is a catalytic factor accepted through targeted programs, policies, and practices by the government and related agencies from the positive perceptions and attitudes of farmers (Islam *et al.,* 2021). The existing legal entity, LMDH, has not been able to serve as a collaborative forum between Perhutani and the community for managing forest land or developing sorghum-eucalyptus agroforestry business. This is because the community observes a lack of diverse activities in LMDH. LMDH only facilitates the coordination between farmers and KTH for land leasing in forest areas owned by routine eucalyptus maintenance activities assigned by Perhutani. Community inclusion is limited to individuals used and compensated by Perhutani. This situation is greatly influenced by the existing working mechanisms, such as the barriers to accessing capital, thereby reducing the environmental sustainability value of sorghum-eucalyptus agroforestry business. Perhutani and the government are not adequately in line with the community interests. This shows the urgent necessity to acknowledge the community as equal partners, thereby promoting the active inclusion in sustaining business and preserving the environment. Haldane *et al*. (2019) stated that private and community partnerships were an important process in learning how to collaborate, describing initiative and active participation to encourage inclusion. A collaborative approach between farmers, government, private sector, scientists, and policymakers plays an important role in promoting agroforestry system in Uttar Pradesh (Divya *et al.,* 2022). To improve independence, the government must facilitate training and institutional development, promote proactive community inclusion in production and marketing processes, and cease the propagation of top-down programs. This shifts the role from passive recipients to active contributors in the development of sorghum-eucalyptus agroforestry business. Enhanced extension services and consistent support, through training and the formation of cooperatives for credit access, are crucial (Oladele *et al.,* 2020). The community acknowledges the potential of sorghum-eucalyptus agroforestry business in enhancing market opportunities, income, and employment. Sorghum, as an important crop, yields the highest net returns compared to others (Ramesh *et al.,* 2023). This commodity can be enhanced for animal feed during dry seasons (Hemida *et al*., 2023). The economic value of sorghum is not only from grain but plant waste processed as animal feed to reduce livestock maintenance costs. The conversion of sorghum plant leaf waste into organic fertilizer and its reintroduction into the land as an ameliorant not only enhances the carrying capacity of forest land but also reduces the reliance on chemical inputs. The development of sorghum production and its related products has been impeded by the lack of consistent guidance and support from both the government and the private sector. Government initiatives, particularly through the Agricultural Office of Majalengka, have focused on providing input for production, without addressing the community's needs in terms of technological and institutional support. The implementation of a sorghum-eucalyptus agroforestry approach has the potential to significantly improve economic, social, and environmental aspects. This requires a synergistic and equitable partnership between the community and the government. Comprehensive guidance and support from the government, spanning from upstream to downstream, including sustainable technologies across economic, social, and environmental dimensions, is essential. The absence of a well-defined business potential indicates that the sustainability assessment in the economic dimension remains low. This economic assessment can serve as an indicator to maintain the sustainability of the business and its environmental dimensions, emphasizing the need for development and support. The concept is closely related to the lack of values in the previous dimensions. Addressing the attributes leading to diminished values invariably improves sustainability and enhances the index in the business and environmental dimensions. Advancements in the attributes of the economic dimension inherently elevate the added value of product development from upstream to downstream. Environmental and business sustainability have the smallest value because the public does not understand the relationship between the dimensions. The economic value of sorghum-eucalyptus business is affected when society is only concerned with gaining economic profits without paying attention to sustainability. The absence of consistent guidance and support from the government and the private sector is one of the causes of the lack of awareness regarding efforts to preserve the forest environment and the use of waste to support conservation. One of the leading factors contributing to the low score is the absence of business activities aimed at using plant waste. The use of agricultural waste provides valuable added value to social, economic, and technological development system (Santoso *et al.*, 2023; Samimi *et al.,* 2023). The cultivation pattern in the eucalyptus agroforestry area is rice-sorghum-sorghum ratoon. Rice husks can be used as material for making biochar applied to agroforestry land. The use of biochar reduces herbicide residues in the soil and environmental pollution (Yavari *et al*., 2022). The management of sorghum product development from upstream to downstream in sorghum-eucalyptus agroforestry area has not been established. Sorghum grains can be processed into various products, including gluten-free flour which is healthier than wheat (Curti *et al*., 2023), raw material for noodles (Akajiaku *et al*., 2017), and wheat substitute flour for making cakes (Bataruic *et al*., 2023). The use of sorghum waste for renewable energy has not been initiated. This commodity is a raw material for bioethanol and is a renewable energy source from biomass (Frankowski *et al*., 2022). In sorghum-eucalyptus agroforestry area, there is potential to develop sorghum-based bioethanol production. The government needs to empower the community in forest areas, through guidance and training related to (a) biochar and organic fertilizer from rice and sorghum waste, (b) development of sorghum-based food processing, and (c) biomass-based renewable energy. The community also gains added value from upstream and downstream processing to increase income and the forest area is maintained. The government and private sector guide the community in collaboration with LMDH for upstream and downstream use of sorghum with the production facilities and marketing of the harvest. The challenges encountered in the implementation share similarities with the issues faced in CBFM. This necessitates the establishment of efficient governance in agroforestry business. The Community-Government and Private Partnership (CGPP) business institutional governance model, as formulated by Komalawati *et al*., (2023), can be applied to address these challenges. The model positions cooperatives as central institutions, regulating organizational and business governance, human resource development, as well as business and environmental sustainability. Cooperatives are placed as central institutions given the community-based formation. Internal and external coordination with stakeholders, including the community, government, and private sector, can improve beneficial partnerships to ensure the preservation and sustainability of forest areas (Komalawati *et al*., 2023). Implementing CGPP under the orchestration of cooperatives, through equal partnerships, can ensure the environmentally sustainable development of sorghum-eucalyptus agroforestry business. This study introduces innovative approaches in assessing the environmental sustainability of the business, using qualitative and quantitative methods across economic, social, and environmental aspects. There are limitations regarding the depth of analysis in each dimension and the specificity of the geographical location of the study, restricting the generalization of results to other contexts. More comprehensive studies are essential to explore other influential variables and broader areas for a holistic understanding of agroforestry environmental sustainability. Future analysis should also benefit from additional data collected through field surveys or in-depth interviews. This study is expected to contribute to the literature on agroforestry and its business governance as well as to inform policy recommendations for the environmentally sustainable development of sorghum-eucalyptus agroforestry and other similar ventures.

CONCLUSION

In conclusion, the novelty of this study was the use of five dimensions, namely business organization, actors, work mechanisms, economic impacts, and environmental sustainability, to evaluate and assess sorghum-eucalyptus agroforestry in a comprehensive and interrelated manner. These five dimensions influenced each other to achieve high sustainability values. The results obtained were: 1) the development of sorghum-eucalyptus agroforestry was economically feasible as shown by the R/C value higher than 1, and 2) the economic profits obtained did not guarantee the sustainability of the business. This was proven by the low sustainability index value in aspects of the role of organization, actors, and working mechanisms, as well as environmental aspects, impacting business sustainability. The challenge for the future was to develop an economically sustainable sorghum-eucalyptus agroforestry business, providing added value to society and having a positive impact on the environment. An unexpected benefit was the added value of upstream-downstream diversification of sorghum. Horizontal diversification of sorghum included processing plant waste into animal feed, organic fertilizer, and renewable energy. Vertical diversification took the form of processing sorghum grain into different processed food products. The problems were related to the institutional governance of sorghum-eucalyptus agroforestry businesses. The establishment of efficient governance with multi-stakeholder partnerships was one of the solutions similar to the issues faced in the CBFM. The inclusion of the community, government, and private sector was not equal in carrying out the sustainability function of each dimension. Further analyses should be directed at appropriate and sustainable institutional governance to realize business and environmental sustainability in agroforestry areas. This study contributed valuable recommendations and insights for policy-making and implementation, showing the urgent need for enhanced cooperative initiatives and institutional reforms to realize the full potential and ensure the environmental sustainability of sorghum-eucalyptus agroforestry business.

AUTHOR CONTRIBUTIONS

Komalawati, the corresponding author, conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts, featuring. S. Hidayat conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts. R.H. Praptana conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts, featuring. M.D. Pertiwi conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts, featuring. A.S. Romdon conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts, featuring. Y. Hidayat conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts, featuring. R.P. Ramadhan conducted the conception, methodology, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts. D. Yuniati conducted the conception, methodology, proper analysis, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts. Saptana conducted the conception, methodology, proper analysis, examination, reviewing, and revising manuscripts. Syahyuti conducted the conception, methodology, proper analysis, examination, reviewing, and revising manuscripts. N. Khaririyatun conducted the examination, wrote the initial draft of the manuscript, reviewing and revised manuscripts, and featured. S. Ika conducted the conception, methodology, examination, reviewing, and revising of manuscripts, featuring. R.K. Jatuningtiyas conducted the examination, wrote the initial draft of the manuscript, and reviewed and revised manuscripts, featuring. Subiharta conducted the conception, methodology, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts. R.N. Hayati conducted the examination, wrote the initial draft of the manuscript, reviewing and revised manuscripts, and featured. Sudarto conducted the conception, methodology, proper analysis, examination, reviewing, and revising manuscripts. M.P. Yufdy conducted the conception, methodology, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts. B. Nuryanto conducted the conception, methodology, examination, reviewing, and revising of manuscripts, featuring. A. Prasetyo conducted the conception, methodology, examination, writing the initial draft of the manuscript, reviewing and revising manuscripts.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. Ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and/or submission, and redundancy, were observed.

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ABBREVIATIONS

%	: Percent
AD/ART	: Memorandum of Association/ Articles of Association
CBFM	: Community-Based Forest Management
CGPP	: Community-Government and Private Partnership
Day/Season	: Per day per season
Day/ha/ season	: Day per hectare per season
FGD	: Focus group discussions
GI	: Gross income
ha	: Hectare
ha/year	: Per hectare per year
IDR	: Indonesian Rupiahs
kg	: Kilogram
kg/ha	: Kilogram per hectare
/kg	: Per kilogram
KPH	: Kuasa Pemangku Hutan (Forest Management Units)
KTH	: Forest farmer groups
LMDH	: Forest Village Community Institution
MCA	: Multi-criteria analysis
MDS	: Multi-dimensional scaling
Men/day	: Men per day
Men/day/ha/ season	: Man day per hectare per season
Mha	: Million hectares
mm	: Millimeter
Perhutani	: State-owned Forestry Company in Indonesia
P_{bp}	: Price of by-product
P_{mp}	: Price of main product
Q_{bp}	: Quantity of by-product
Q_{mp}	: Quantity of main product
R^2	: R Square is used to identify the influence of independent variables on dependent variable
Rapfish	: Rapid Appraisal of Fisheries
R/C	: Revenue per cost
RMS	: Root mean square
SK Kulin KK	: Surat Keterangan Pengakuan dan Perlindungan Kemitraan Kehutanan (Forestry partnership recognition and protection decree)
SQR	: Square correlation
USD	: United States of America's Dollar
/years	: Per year

REFERENCES

Abdel-Ghany, S.E.; Ullah, F.; Ben-Hur, A.; Reddy, A.S.N., (2020). Transcriptome analysis of drought-resistant and drought-sensitive sorghum (Sorghum bicolor) genotypes in response to peg-induced drought stress. Int. J. Mol. Sci., 21(3): 772 **(26 pages)**.

Adeyeye, S.A.O., (2016). Assessment of quality and sensory properties of sorghum–wheat flour cookies. Cogent Food Agric., 2: 1245059 **(10 pages)**.

Aduwo, O.E.; Aransiola, J.O.; Ikuteyijo, L.O.; Alao, O.T.; Deji, O.F.; Ayinde, J.O.; Adebooye, O.C.; Oyedele, D. J., (2017). Gender differences in agricultural technology adoption in developing countries: a systematic review. Afr. Veg. Forum Acta Hortic., 1238: 227-238 **(12 pages)**.

Ahmad, S.; Xu, H.; Ekanayake, E.M.B.P., (2023). Socioeconomic Determinants and Perceptions of Smallholder Farmers towards Agroforestry Adoption in Northern Irrigated Plain, Pakistan. Land. 12: 813 **(25 pages)**.

Ahmad, S.; Zhang, C.; Ekanayake, E.M.B.P., (2021). Smallholder farmers' perception on ecological impacts of agroforestry: evidence from northern irrigated plain, Pakistan. Pol. J. Environ. Stud., 30(4): 2969–2979 **(11 pages)**.

Aisharya, I.Y.; Gunawan, B.; Abdoellah, O.S.; Gunawan, W.; Dewa J.J.P.K., (2022). Role and interaction between local actors in community-based forest management in Upper Citarum Hulu. J. Pengelolaan Sumberdaya Alam dan Lingkungan. 12(2): 335-351 **(18 pages)**.

Akajiaku, L.O.; Nwosu, J.N.; Kabuo, N.O.; Odimegwu, E.N.; Umelo, M.C.; Unegbu, V.C., (2017). Using sorghum flour as part substitute of wheat flour in noodles making. MOJ Food Process. Technol., 5(2): 250–257 (**8 pages**).

Akbar, M.F.; Fawwaz, M.I., (2022). The effect of rice field area, land ownership status, and religiosity on rice farmers'income in Pujon District. Int. J. Adv. Tech. Eng. Inf. Syst., 1(1): 11–24 **(14 pages)**.

Akter, R.; Hasan, M.K.; Kabir, K.H.; Darr, D.; Roshni, N.A., (2022). Agroforestry systems and their impact on livelihood improvement of tribal farmers in a tropical moist deciduous forest in Bangladesh. Trees For. People, 9: 100315 **(9 pages)**.

Al Majzoub, R.; Khaled, S.; El Khatib, S.; Krayem, M., (2023). A comparison between wheat and sorghum flour in biscuits application: A review. Food Sci. Eng., 4(1): 89–102 **(14 pages)**.

Awazi, N.P.; Temgoua, L.F.; Tientcheu-Avana, M.L.; Chimi, D.C.; Tchamba, M.N., (2023). Climate change and peasant farmers' adoption of multifunctional agroforestry systems in Cameroon: Determinants and policy ramifications. Forestist. 73(2): 117–130 **(14 pages)**.

Awe, F.; Olayemi, O.T.; Olatunji, B.T., (2021). Determinants of farmers' adoption of agroforestry technology in Ibarapa Area of Oyo State, Nigeria. J. Agric. Food Sci., 19(1): 189–200 **(12 pages)**.

Aziza, M.F.; Kartika, R.D.; Prameswara, B.; Furqan, A., (2023). The Role of Local Champions in the Development of Community Based Tourism in Ponggok Village, Klaten. J. Res. Soc. Sci. Econ. Manage., 2(12): 2900-2910 **(11 pages)**.

Bank Indonesia, (2023). Bank Indonesia Transaction Exchange.

Batariuc, A.; Cotovanu, I.; Mironeasa, S., (2023). Sorghum Flour Features Related to Dry Heat Treatment and Milling. Foods. 12: 2248 **(20 pages).**

Chakma, K.; Ruba, U.B., (2021). Role of Bangladeshi women in diverse agricultural production: A review. Eur. J. Agric. Food Sci.**,** 3(3): 1–5 **(5 pages)**.

Chavula, P.; Turyasingura, B., (2023). contribution of sorghum production to smallholder farmers' welfare in Rubanda District, Uganda. Int. J. Agric. Econ., 8(3): 98–101 **(4 pages)**.

Chete, O.B., (2019). Gender and agricultural practice in developing countries: Literature review. South Asian J. Soc. Stud. Econ.**,** 5(2): 1–11 **(11 pages)**.

Cirella, G.T.; Anatoliy, G.G.; Storto, C.; Russo, A., (2020). Exploring social sustainability and economic practices: Multi-journal compedium. Sustainability. 12: 1718 (**7 pages**).

Cock, J.; Jiménez, D.; Dorado, H.; Oberthür, T., (2023). Operations research and machine learning to manage risk and optimize production practices in agriculture: good and bad experience. Curr. Opin. Environ. Sustainable. 62: 101278 **(10 pages)**.

Curti, M.I.; Palavecino, P.M.; Savio, M.; Baroni, M.V.; Ribotta, P.D., (2023). Sorghum (Sorghum bicolor L. Moench) Gluten-Free Bread: The Effect of Milling Conditions on the Technological Properties and In Vitro Bioaccessibility of Polyphenols and Minerals. Foods. 12: 3030 **(19 pages).**

Fahmi, M.K.M.; Dafa-Alla, D.A.M.; Kanninen, M.; Luukkanen, O., (2018). Impact of agroforestry parklands on crop yield and income generation: case study of rainfed farming in the semi-arid zone of Sudan. Agrofor. Syst.**,** 92: 785–800 **(16 pages)**.

Fauzi, A.; Anna, Z., (2022). Evaluasi status keberlanjutan pembangunan perikanan: aplikasi pendekatan rapfish (Studi Kasus Perairan Pesisir DKI Jakarta). J. Pesisir dan Lautan. 4(3): 43–55 **(13 pages)**.

Frankowski, J.; Wawro, A.; Batog, J.; Szambelan, K.; Łacka, A., (2022). Bioethanol Production Efficiency from Sorghum Waste Biomass. Energies. 15: 3132 **(11 pages)**.

Divya, B.; Daniel, S.; Raj, A.J.; Saritha, J.D., (2022). Adaptation reasons for agroforestry in the study area of Eastern Uttar Pradesh, India. Int. J. Environ. Clim. Chang., 12(12): 521–528 **(8 pages)**.

Dou, Y.; Li, Y.; Li, M.; Chen, X.; Zhao, X., (2023). The role of agroforestry in poverty alleviation: a case study from Nujiang Prefecture, Southwestern China. Sustainability. 15(15): 12090 **(20 pages)**.

Dube, F.; Maphosa, M., (2022). Significance of sweet sorghum as a multi-purpose crop for sub-Saharan Africa. Afr. Crop Sci. J., 30(2): 235–243 **(9 pages)**.

Duffy, C.; Toth, G.G.; Hagan, R.P.; McKeown, P.C.; Rahman, S.A.; Widyaningsih, Y.; Sunderland, T.C.H.; Spillane, C., (2021). Agroforestry contributions to smallholder farmer food security in Indonesia. Agrofor. Sys., 95(6): 1109–1124 **(16 pages)**.

Dwivedi, S.; Puria, P.; Kumari, S.S.; Kumar, A., (2023). Environmental Protection through Agroforestry. Just Agric., 3(11): 120–124 **(5 pages)**.

Gautam, Y.; Singh, P.K.; Singh, O.P., (2021). Financial profitability and resource use efficiency in sorghum production under rainfed conditions. J. Pharmacogn. Phytochem., 10(1): 106–109 **(4 pages)**.

Ginwal, D.S.; Kumar, R.; Ram, H.; Meena, R.K.; Yadav, M.R.; Makarana, G.; Chauhan, A.; Manjunath, S.K.; Kumar, U., (2021). Evaluation of productivity and quality of forage sorghum and legumes cropsunder varying intercropping combinations. Indian J. Anim. Sci**.,** 91(9): 754–759 **(6 pages)**.

Ghosh, M.K.; Karim, M.R.; Orpita, F.U.R.; Jahan, M.L.; Simi, F.; Sony, M.A.A., (2023). Exploring Farmers Perspectives on Modern Agricultural Technology: A Study in Chapainawabganj District. Eur. J. Agric. Food Sci., 5 (4): 19–27 **(9 pages)**.

Hajjar, R.; Oldekop, J. A.; Cronkleton, P.; Newton, P.; Russell, A. J.; Zhou, W., (2021). A global analysis of the social and environmental outcomes of community forests. Nat. Sustainability. 4: 216–224 **(9 pages)**.

Haldane, V.; Chuah, F.L.H.; Srivastava, A.; Singh, S.R.; Koh, G.C.H.; Seng, C.K.; Legido-Quigley, H., (2019). Community participation in health services development, implementation, and evaluation: A systematic review of empowerment, health, community, and process outcomes. PLoS ONE. 14(5): e0216112 **(25 pages).**

Hasan, K.; Aftah, R.M.; Syakban, M.N., (2022). Digital skills in the optimization of agricultural technology among milenial 2022 (Description Study on Agricultural Students at Malikussaleh University). Proceedings of International Conference on Social Science, Political Science, and Humanities (ICoSPOLHUM)**,** 3: 1–10 **(10 pages)**.

Hemida, M.; Vityi, A.; Hammad, Z.M., (2023). Socio-economic traits and constraints associated with smallholder farmers in Taungya agroforestry program in Sudan. Agrofor. Syst., 97: 1169–1184 **(16 pages)**.

Ibrahim, I.I.; Nabage, O.H.A., (2023). Factors Influencing adoption of agroforestry farming system as a means for sustainable environmental conservation method in Jere Lga, Borno State, Nigeria. J. Agripreneur. Sustanable Dev., 6(2): 89–100 **(12 pages)**.

Indonesian of Statistics, (2019). Statistical Yearbook of Indonesia 2019; Indonesian of Statistics: Jakarta, Indonesia **(738 Pages)**.

Islam, Md.A.; Aktar, L.A.; Jubair, S.M.R.; Dey, T.; Biswas, R., (2021). Constraints to adopt agroforestry adjacent to the coastal belt of sundarbans, Banglades. Eur. J. Agric. Food Sci., 3(4): 78–88 **(11 pages)**.

Kamal, M.; Ahmed, R.; Alam, W.; Ali, N., (2023). Maximizing productivity and sustainability of land through agroforestry: insights into knowledge, perceptions, and economic benefits. Agric. Mech. Asia Afr. Latin Amer., 54(3): 12501–12518 **(20 pages)**.

Kang, D.; Evans, J., (2020). Against method: Exploding the boundary between qualitative and quantitative studies of science. Quant. Sci. Stud., 1(3) 930–944 **(15 pages)**.

Kaushal, G.S.; Raj, A.J.; Kumar, H.; Khare, N.; Masih, S.; Umrao, R., (2023). Assessment of the agroforestry system on farmers socioeconomic status in Azamgarh District, Uttar Pradesh, India. Int. J. Environ. Clim. Chang., 13(6): 476–483 **(8 pages)**.

Kavanagh, P.; Pitcher, T., (2004). Implementing Microsoft Excel Software for Rapfish: A technique for the Rapid Apprasial of Fisheries Status. Fish. Cen. Res. Rep**.,** 12(2): 1–75 **(75 pages)**.

Kemenkoekonomi, (2022). Dimulainya pilot project pengembangan sorgum menandai upaya substitusi dan diversifikasi dalam penguatan ketahanan pangan.

Kertajati of Statistic, (2022). Kertajati Subdistric in Figure 2022. Majalengka of Statistic, Majalengka, Indonesia **(80 pages)**.

Komalawati, K.; Hidayat, S.; Praptana, R.H.; Pertiwi, M.D.; Romdon, A.S.; Hidayat, Y.; Yuniati, D.; Syahyuti; Ramadhan, R.P.; Saptana; Indrawanto, C., (2023). Community-government, and private partnership (CGPP): revisiting the concept of community-based forest management. Int. For. Rev., 25(3): 310–326 **(17 pages)**.

Kumar, V.; Bahukhandi, D.; Wasnik, V.K., (2017). An economic analysis of sorghum seed production: A profitable enterprise for farmers. Agron. Econ. Int. J., 4(1): 11–14 **(4 pages)**.

Kumar, A.; Singh, A.K.; Kumar, S.; Kumar, S.; Kisku, U.; Rajawat, B.S.; Kushwaha, N.K., (2023). Structural analysis of agroforestry practices on farmer field in Jaunpur District of Uttar Pradesh. Ann. For. Res., 66(1): 3949–3962 **(14 pages)**.

Lai, J.; Widmar, N.J.O.; Gunderson, M.A.; Widmar, D.A.; Ortega, D.L., (2018). Prioritization of farm success factors by commercial farm managers. Int. Food Agribus. Manage. Rev., 21(6): 817-832 **(16 pages)**.

Lei, S.; Qiao, Q.; Gao, X.; Feng, J.; Wen, Y.; Han, Y., (2023). Ecological awareness, policy perception, and green production behaviors of farmers living in or near protected areas. Forests. 14(7): 1339 **(16 pages)**.

Liu, H.; Lantian, R.; Huub, S.; Yongbin, Z.; Guang H.X., (2015). An economic analysis of sweet sorghum cultivation for ethanol production in North China. Gcb Bioenergy. 7(5): 1176–1184 **(9 pages)**.

Ma, J.; Chen, S., (2022). Does land transfer have an impact on land use efficiency? A case study on rural China. Nat. Acc. Rev., 4(2): 112–134 **(23 pages)**.

Mahmood, M.I.; Zubair, M., (2020). Farmer's perception of and factors influencing agroforestry practices in the Indus River Basin, Pakistan. Small-Scale For., 19: 107–122 **(16 pages)**.

McCuistion, K.C.; Selle, P.H.; Liu, S.Y.; Goodband, R.D., (2019). Sorghum as a feed grain for animal production. Sorghum Millets. 355–391 **(37 pages)**.

McGunnigle, N.; Bardsley, D.; Nuberg, I.; Cedamon, E.; Pandit, B.H., (2023). The succession of farmers' perceptions of transitioning landscapes – a case study of agroforestry in the middle hills of Nepal. Hum. Ecol., 51: 1–19 **(19 pages)**.

Majalengka of Statistic, (2023). Majalengka Regency in Figures 2023. Majalengka of Statistic, Majalengka Indonesia **(318 pages)**.

Malherbe, S.J.; Cripwell, R.A.; Favaro, L.; van Zyl, W.H.; Viljoen-Bloom, M., (2023). Triticale and sorghum as feedstock for bioethanol production via consolidated bioprocessing. Renewable Energy. 206: 498–505 **(8 pages).**

Mayele, J.M.; Bongo, A.L., (2022). The community perceptions and attitudes about agroforestry and impediments to on-farm trees/ shrubs growing and management in Rajaf County-South Sudan. Int. J. Innov. Sci. Res. Tech., 7(3): 994–1004 **(11 pages)**.

Meena, G.L.; Sharma, L.; Singh, H.; Bairwa, K.C.; Kumar, K., (2023). Cost and return analysis of kharif sorghum (sorghum bicolor) in Bhilwara District, Rajasthan. Agric. Sci. Digest-A Res. J.**,** 43(2) 196–200 **(5 pages)**.

Mottaleb, K.A.; Kruseman, G.; Snapp, S., (2022). Potential impacts of Ukraine-Russia armed conflict on global wheat food security: A quantitative exploration. Global Food Sec., 35(2022): 100659 (**12 pages**).

Ninh, L.K., (2021). Economic role of education in agriculture: Evidence from rural Vietnam. J. Econ. Dev., 23 (1): 47–58 **(12 pages)**.

Ndubi, J.; Murithi, F.; Thuranira, E.; Murage, A.; Kathurima, C.; Gichuru, E., (2023). Gender mainstreaming in miraa farming in the eastern highlands of Kenya. Sustainability. 15(15): 12006 **(14 pages)**.

Ngango, J.; Musabanganji, E.; Maniriho, A.; Nkikabahizi, F.; Mukamuhire, A., (2023). Examining the adoption of agroforestry in Southern Rwanda: a double hurdle approach. For. Sci. Technol., 1–8 **(8 pages)**.

Octavia, D.; Suharti, S.; Dharmawan, I.W.S.; Nugroho, H.Y.S.H.; Supriyanto, B., Rohadi, D.; Mindawati, N., (2022). Mainstreaming smart agroforestry for social forestry implementation to support sustainable development goals in indonesia: A review. Sustainability. 14(15): 9313 **(29 pages)**.

Oladele, O.N.; Emeghara, U.U.; Ishola, B.F.; Ayodele, J.T.; Awobona, T.A.; Olukotun, O., (2020). Adoption of agroforestry practices by arable farmers in igabi local government area of Kaduna State, Nigeria. Asian J. Res. Agric. For., 6(2): 28–37 **(10 pages)**.

Osibanjo, A.A.; Ibidapo, P.O.; Efuribe, N.E.; Elemo, G.N., (2022). Breadmaking potential of sorghum flour and sorghum bran. Int. J. Food Sci. Agric., 6(3): 267–271 **(5 pages)**.

Quisumbing, A.R.; Meinzen-Dick, R.; Raney, T.L.; Croppenstedt, A.; Behrman, J.A.; Peterman, A., (2014). Closing the knowledge gap on gender in agriculture. Gender Agric., 1238: 3–27 **(25 pages)**.

Parnabhakti, L.; Puspaningtyas, N.D., (2021). Persepsi Peserta Didik Pada Media Powerpoint Dalam Google Classroom. J. Ilmiah Matematika Realistik. 2(1): 18–25 **(8 pages)**.

Pathania, A.; Chaudhary, R.; Samriti; Sharma, S.; Kumar, K., (2020). Farmers' perception in the adoption of agroforestry practices in low hills of Himachal Pradesh. Indian J. Agrofor., 22(2): 101–104 **(4 pages)**.

Perhutani, (2022). Public Sumary KPH Majalengka Tahun 2022. Perum Perhutani Divisi Regional Jawa Barat dan Banten KPH Majalengka, Majalengka Indonesia (**33 pages**).

Ramadhan, R.; Syah, D.F.; Waskhito, N.T., (2022). Effectiveness and Institutional Conditions in Social Forestry Program: Case Study of Forest Village Community Institution (LMDH) Sumber Makmur, Forest Management Unit (KPH) Malange. J. Sylva Lestari. 10(1): 141–154 **(14 pages)**.

Ramesh, K.R.; Deshmukh, H.K.; Sivakumar, K.; Guleria, V.; Umedsinh, R.D.; Krishnakumar, N.; Thangamalar, A.; Suganya, K.; Kiruba, M.; Selvan, T.; Balasubramanian, P.; Ushamalini, C.; Thiyagarajan, G.; Vincent, S.; Rajeswari, P.; Bavish, S.; Riaz, A.; Senthil, K., (2023). Influence of eucalyptus agroforestry on crop yields, soil properties, and system economics in Southern Regions of India. Sustainability. 15(4): 3797 **(20 pages)**.

Ratnawati, D.; Vivianti, V., (2020). Persepsi Mahasiswa Terhadap Pembelajaran Daring pada Mata Kuliah Praktik Aplikasi Teknologi Informasi. J. Edukasi Elektro. 4(2): 110–119 **(10 pages)**.

Saha, S.; Sharmin, A.; Biswas, R.; Md. Ashaduzzaman., (2018). Farmers' perception and adoption of agroforestry practices in Faridpur District of Bangladesh. Int. J. Environ. Agric. Biotechnol., 3(6): 1987–1994 **(8 pages)**.

Salaz-Zapata, W.A.; Ortiz-Munoz, S.M., (2018). Analysis of meanings of the concept of sustainability. Sust. Dev., 27(1): 153–161 (**9 pages**).

San, S.M.; Kumar, N.; Biber-Freudenberger, L.; Schmitt, C.B., (2023). Agroforestry-based community forestry as a large-scale strategy to reforest agricultural encroachment areas in Myanmar: ambition vs. local reality. Ann. For. Sci., 80(27): 1–15 **(15 pages)**.

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Santoso, A.; Arianti, F.; Rohaeni, E.; Haryanto, B.; Pertiwi, M.; Panggabean, L.; Prabowo, A.; Sundari, S.; Wijayanti, S.; Djarot, I.; Kurniawati, F.; Sahwan, F.; Prasetyo, T.; Barkah, A.; Adibroto, T.; Ridlo, R.; Febijanto, I.; Wasil, A.; Lusiana, S.; Rosmeika, R.; Heryanto, R., (2023). Sustainability index analysis of organic fertilizer production from paunch manure and rice straw waste. Global J. Environ. Sci. Manage., 9(SI): Eco-Friendly Sustainable Management): 193-218 **(26 pages)**.

Sari, E.N.; Harsono, P.; Supriyono, S., (2022). Response of sorghum variety growth in the first ratoon with liquid organic fertilizer application. E3S Web of Conference. 361: 04004 **(6 pages)**.

Sarveswaran, S.; Johar, V.; Singh, V.; Raghunanyhan, C., (2023). Agroforestry: A Way Forward for Sustainable Development. Econ. Environ. Cons., 29(Supplement): 300–309 **(10 pages)**.

Sibanda, T.; Ncube, T.; Ngoromani, N., (2015). Rheological properties and bread making quality of white grain sorghum-wheat flour composites. Int. J. Food Sci. Nut. Engineer., 5(4): 176–182 (**7 pages**).

Shukla, A.K.; Chandra, K.K.; Singh, A.K., (2021). Agroforestry practices in riparian ecology and its benefits to the farmers of Central Chhattisgarh. Chhattisgarh J. Sci. Tech., 18(3): 86–89 **(4 pages)**.

Statistic Indonesia., (2023). Impor Biji Gandum dan Meslin menurut Negara Asal Utama, 2017-2022.

Sulasni, P.; Suwendra, I.W., (2021). The influence of income and number of family members on the welfare of farming families in Gerokgak Village, Gerokgak District. J. Akuntansi Profesi, 2(1): 506–513 **(8 pages)**.

Sukwika, T.; Darusman, D.; Kusmana, C.; Nurrochmat, D.R., (2016). Evaluating the level of sustainability of privately managed forest in Bogor, Indonesia. Biodivers. J. Biol. Div., 17(1): 241–248 **(8 pages)**.

Syuryawati; Suwarti; Marcia, B. P., (2020). Utilization of sweet sorghum biomass for profitable feed and bioethanol. IOP Conference Series: Earth Environ. Sci., 484: 012120 **(10 pages)**.

Tega, M.; Bojago, E., (2023). Farmer's perceptions of agroforestry practices, contributions to rural household farm income, and their determinants in Sodo Zuria District, Southern Ethiopia. Int. J. For. Res., 5439171 **(19 pages)**.

Tokede, A.M.; Banjo, A.A.; Ahmad, A.O.; Akanni, O.F.; Olumide-Ojo, O., (2020). Perception of farmers on agroforestry systems adoption in Akinyele Local Government Area, Ibadan, Oyo State, Nigeria. J. Res. For. Wildlife Environ., 12(3): 235–242 **(8 pages).**

Widiyanto, A.; Fauziyah, E.; Suhartono., (2022) The evaluation of agroforestry development in marginal land area of Gunungkidul, Indonesia. IOP Conference Series: Earth Environ. Sci., 1109: 012090 **(10 pages)**.

Wienhold, K.; Goulao, L.F., (2023). The embedded agroecology of coffee agroforestry: a contextualized review of smallholder farmers' adoption and resistance. Sustainability. 15(8): 6827 **(30 pages)**.

Wijayanto, H.W.; Lo, K.-A.; Toiba, H.; Rahman, M.S., (2022). Does Agroforestry Adoption Affect Subjective Well-Being? Empirical

Evidence from Smallholder Farmers in East Java, Indonesia. Sustainability. 14(16): 10382 **(10 pages)**.

Wondimenh, S., (2023) The contribution of traditional agroforestry systems and challenges of adoption by smallholder farmers in Ethiopia. A review. East Afr. J. For. Agrofor., 6(1): 18–32 **(15 pages)**.

Yavari, S.; Kamyab, H.; Manan, T.S.B.A.; Chelliapan, S.; Asadpour, R.; Yavari, S.; Sapari, N.B.; Baloo, L.; Sidik, A.B.C.; Kirpichnikova, I., (2022). Bio-efficacy of imidazolinones in weed control in a tropical paddy soil amended with optimized agrowaste-derived biochars. Chemosphere. 303(1): 134957 **(8 pages).**

Zhou, L., (2022). Qualitative comparative analysis (QCA): An innovative approach for Integrating qualitative and quantitative analysis. Best Ev. Chinese Edu., 10(2): 1353–1355 **(3 pages)**.

Zhou, Y.; Huang, J.; Li, Z.; Wu, Y.; Zhang, J.; Zhang, Y., (2022). Yield and quality in main and ratoon crops of grain sorghum under different nitrogen rates and planting densities. Front. Plant Sci., 12: 778663 **(10 pages)**.

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ORIGINAL RESEARCH PAPER

Synergistic removal of organic and nutrients from landfill leachate using photobioreactor-cultivated microalgae-bacteria consortium

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ABSTRACT

BACKGROUND AND OBJECTIVES: The utilization of stabilization pond system for landfill leachate treatment is hindered by its requirement for expansive land areas and extended retention periods. Although the system effectively removes organic compounds, its ability to eliminate nutrients such as nitrogen and phosphorus is comparatively limited. Consequently, the leachate subjected to treatment often falls short of meeting the mandated standards for effluent quality. In response to this challenge, a research study was undertaken to investigate the potential of utilizing a consortium comprising microalgae and bacteria in the treatment of landfill leachate.

METHODS: The microalgae, bacteria, and leachate utilized in this study were sourced from a leachate treatment facility located at the Aceh regional domestic waste management unit in Blang Bintang, Aceh Besar, Indonesia. The two glass photobioreactors were operated batch-wise, where the first was provided with a combination of air and carbon dioxide, and the other was solely exposed to air. The pollutant removal efficacy in the leachate effluent was assessed through the measurements of chemical oxygen demand, ammonia, nitrate, nitrite, and phosphate concentrations. Subsequently, macroscopic identification of microalgae and bacteria species was also conducted.

FINDINGS: Utilizing a consortium of microalgae and bacteria has demonstrated efficacy in treating leachate, resulting in a notable reduction of contaminants within the effluent. The symbiotic association between microalgae and bacteria in the context of leachate waste treatment is evident. The bacteria's metabolic actions result in carbon dioxide emission, which subsequently serves as a substrate for the photosynthetic activities of the microalgae. The microalgae facilitate the transfer of oxygen, produced through photosynthesis, to the bacteria to support their metabolic processes. Therefore, introducing exogenous carbon dioxide to the consortium yields minimal discernible effects, given that the bacteria adequately fulfill the carbon dioxide requirements of the microalgae. This discovery enhances the efficacy of leachate treatment techniques by leveraging the utilization of pre-existing mixed cultures of microalgae and bacteria found in leachate facilities.

CONCLUSION: This study evaluated the microalgae-bacteria consortium's effectiveness in reducing leachate pollutants. The consortium exhibited a significant capability, achieving a 75 percent reduction in chemical oxygen demand and successfully eliminating a range of contaminants. Additionally, it demonstrated effective removal of nitrogen compounds such as ammonia, nitrate, and nitrite, with removal rates reaching 75 percent. Notably, the consortium showed a 99 percent removal rate for phosphate compounds. Even with the introduction of carbon dioxide, the pollutant removal remained consistently high, suggesting that the addition of carbon dioxide did not significantly influence the overall process.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
69	4	3

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INTRODUCTION

The issue of domestic solid waste management is still a prominent concern in Indonesia and other undeveloped or developing countries due to the absence of environmentally sustainable waste management practices (Ratnawati *et al.,* 2023; Samimi and Nouri, 2023). In 2020, domestic waste production in Indonesia was 67.8 million tons, with approximately 90 percent (%) in landfills. Regarding operational efficiency and fiscal considerations, landfilling is the simplest and most cost-effective method of solid waste disposal (Munawar and Fellner, 2013). The degradation of waste in landfills emits gases such as methane and carbon dioxide (CO_2), which intensify the issue of global warming. Furthermore, it generates by-products in the form of liquid leachate, potentially contaminating the surrounding groundwater and soil. Despite the availability and continuous development of multiple systems to use energy from landfill gas (Munawar and Fellner, 2013), extracting energy or products from landfill leachate remains exceedingly uncommon. Leachate is a liquid waste product originating when external fluids such as rainwater, surface runoff, and other liquids come into contact with landfill waste, causing dissolution and the washing away of dissolved substances. This includes organic materials stemming from the biological decomposition process. Generally, leachate is classified as hazardous liquid waste due to the elevated levels of biological oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH_3), and nitrogen (Zhu *et al*., 2019; Ahmed *et al*., 2018; Samimi and Shahriari Moghadam, 2018), with variations depending on the age of the landfill. It also contains toxic heavy metals (Xaypanya *et al*., 2018), necessitating treatment before being discharged into receiving water bodies. The prevalent treatment method in the country uses a pond system technology, with several stages such as collection, aerobic, and stabilization ponds. A key challenge posed by this pond treatment approach is the need for a relatively extended residence time, approximately spanning from 30 to 50 days, and a significant land area to accommodate the required facilities. This method effectively eliminates a significant portion of the organic matter and certain nutrients present in leachate. However, considerable nitrogen levels in the form of nitrate (NO_3) and phosphorus persist in the treated water, posing difficulties for bacterial nutrient removal. Consequently, the treated leachate frequently falls short of meeting the quality standards required for the release into water bodies, as stipulated by local environmental agencies. This phenomenon occurs due to excessive nitrogen content in the effluent, surpassing permissible limits. The discharge of surplus nutrient into natural water bodies poses the risk of inducing eutrophication in aquatic ecosystems, resulting in habitat degradation for aquatic flora and fauna due to the depletion of dissolved oxygen. Moreover, the integration of supplementary units for nutrient removal presents operational challenges. This is attributed to the low concentration of organics, leading to high investments and operating expenses. Due to the inherent simplicity and cost-effectiveness, stabilization ponds remain the preferred option for treating landfill leachate in most underdeveloped and developing countries (Arun *et al*., 2020; Amit *et al*., 2020). Recently, there has been an increasing scholarly focus on using microalgae for wastewater treatment, including leachate (Shahid *et al*., 2020; Aditya *et al*., 2022). This is because most wastewater contains nitrogen and phosphorus, with suitable growing conditions for microalgae growth. The approach can minimize the costs associated with removing nitrogen and phosphorus compounds (Kamyab *et al*., 2018) while generating valuable biomass as a by-product. The environmental problems of greenhouse gas emission are addressed by capturing CO_2 gas as the carbon source for growth (Srimongkol *et al*., 2022). Passing CO_2-rich gases across microalgae-based wastewater treatment systems proves to be a highly efficient method of extracting CO_2 and removing nutrients from liquid waste, simultaneously enhancing microalgae biomass growth at a minimal cost. This shows that the use of microalgae biomass offers significant economic and industrial prospects in serving as fundamental resources for the synthesis of medicinal compounds, food sources (Moejes and Moejes, 2017), energy production (Zaman *et al*., 2020) and other valuable products. In wastewater treatment, microalgae can be used to reduce pollutant concentrations and enhance biomass growth for potential conversion into economically viable products. Although the use of microalgae-bacteria consortium in wastewater treatment has gained significant attention globally, there is limited information on its application in treating landfill leachate in tropical countries. The use of cultures derived directly from leachate ponds can potentially reduce the acclimatization period for microalgae and bacteria, thereby enhancing efficiency. Sourcing cultures directly from leachate facilities ensures that the isolated species are highly adapted to the specific circumstances of the effluent requiring treatment. Consequently, this study aimed to investigate and validate the effectiveness of microalgae-bacteria consortium extracted from leachate treatment ponds in removing pollutants. The experiment focused on assessing the capability of the consortium to eliminate organic matter, nitrogen, and phosphate (PO_4) compounds from leachate collected from the treatment plant located at the Provincial Domestic Waste Management Unit in Blang Bintang, Aceh Besar District, Indonesia. This study was conducted at the Environmental Engineering Laboratory in the Chemical Engineering Department at Syiah Kuala University in Banda Aceh, Indonesia, in 2022. This study sought to enhance our understanding of the performance and potential of the consortium as a sustainable solution for addressing the intricate challenges associated with landfill leachate treatment in tropical regions.

MATERIALS AND METHODS

Leachate, bacteria, and microalgae used in this study were obtained directly from a leachate treatment pond managed by Aceh Regional Waste Management Agency in Blang Bintang, Aceh Besar, Indonesia. Moreover, using resources directly from the actual treatment ponds ensured the experimental conditions were similar to real-world circumstances. By sourcing components from the pond system, this study aimed to generate results and data representing leachate properties in the tropics.

Microalgae-bacteria culture and analysis

The bacterial culture was sourced from the aerated lagoon located at the Provincial Domestic Waste Management Unit in Blang Bintang. Subsequently, the bacterial culture was isolated before its application in the photobioreactor experiment through the pour method, using nutrient broth media (Merck). After the implementation of the isolation protocol, the bacterial culture was subjected to a controlled incubation period for two days in an incubator at a temperature of 28 degrees Celsius (°C) (Tighiri and Erkurt, 2019).

Microalgae samples were also obtained from the Regional Waste Management Unit at the final stabilization pond of the landfill leachate treatment plant, where the treated leachate is ready for discharge into the environment. Microalgae was subjected to cultivation in Erlenmeyer flasks using BG-11 medium for 14 days. In the cultivation period, the light intensity maintained a level of 2,600 lux, operating under a 12-hour light-dark cycle (Emalya *et al*., 2023). Microalgae and bacteria species were identified using conventional methods by examining individual cell morphology or colony characteristics. Due to the reliability of the established phenotypic parameters, the characterization and identification of the microalgae-bacteria consortium were conducted using a light microscope (Wolfe) at a magnification of 400x. The collected data were cross-referenced with a comprehensive reference compendium designed explicitly for identifying microalgae and bacteria (Holt, 1994). This procedural measure facilitated a thorough analysis and verification of the results, guaranteeing precision and dependability. Microalgae-bacteria abundance was calculated based on the procedure used in Effendi *et al*. (2016) with slight modifications as expressed in Eq. 1.

$$N = F\,x\frac{Vt}{Vs}x\frac{1}{Vd} \tag{1}$$

Where *N* is the total abundance of biota in individuals per liter (ind./L), *F* is the number of observed biota in individuals (ind.), *Vt* is the volume of filtered water in liters (L), *Vs* is the volume of filtered water sample in liters (L), and *Vd* is the volume of the sample filtered in liters (L). The results of microalgae-bacteria consortium analysis and abundance are presented in Table 3.

Landfill leachate sampling

The landfill leachate used in this study was sourced from the latest stabilization lagoon of the Regional Waste Management Unit. This selection was based on the consideration that the strength of leachate from the collection pond would require a longer period for the microalgae-bacteria consortium to acclimate. A cumulative quantity of 20 liter (L) landfill leachate was obtained and carefully preserved in sanitized containers before being transported to the laboratory. Subsequently, the sample was securely stored in a freezer at approximately a temperature of 4°C. Leachate from the stabilization pond had BOD and COD concentrations of 117 milligrams per liter (mg/L) and

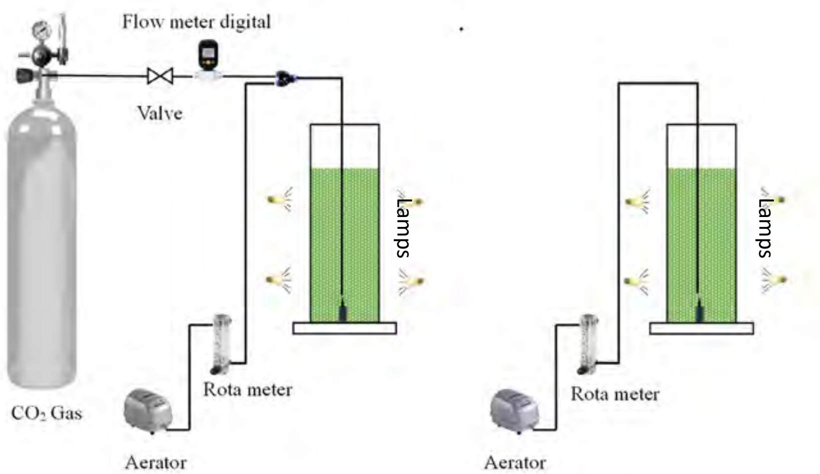

Fig. 1: Experimental photobioreactors arrangement

350 mg/L, containing 243 mg/L NH_3, 294 mg/L NO_3, and 337 mg/L nitrite (NO_2). The initial concentrations of iron (Fe), manganese (Mn), and zinc (Zn) before discharge were 6.4 mg/L, 1.8 mg/L, and 6.8 mg/L, respectively. Before operating the photobioreactor, the concentrations of pollutants in leachate were reassessed. The concentrations of COD, NH_3, NO_3, NO_2, and PO_4 at the start of photobioreactor operation were recorded as 233 mg/L, 29 mg/L, 63 mg/L, 85 mg/L, and 1.157 mg/L, respectively.

Experimental Setup

A total of two photobioreactors were operated in batch mode with distinct aeration conditions. Photobioreactors represent a category of bioreactors designed to utilize light as an energy source for cultivating phototrophic microorganisms, including microalgae, cyanobacteria, and purple non-sulfur bacteria. The first photobioreactor was performed by introducing a combination of air and pure CO_2 gas, with CO_2 gas constituting 2% of the total airflow. Meanwhile, the second photobioreactor was exclusively supplied with air at a rate of 1 L/min. Photobioreactors were fabricated using glass material, with dimensions of 40 centimeters (cm) in height and 10 cm in diameter, yielding a combined volume of 2,500 milliliters (mL). The schematic representation is presented in Fig. 1. Vertically installed two fluorescent lamps (8 Watt) emitting a light intensity of 2,600 lux served as the light source, adhering to a 12:12 light-dark cycle regulated by a digital timer socket. Moreover, photobioreactors featured provisions including an aerator, cylinders containing pure CO_2 gas, and a gas mixer to blend air and CO_2. The mixture obtained was supplied to the reactor through a sparger positioned at the lower section of photobioreactors. For the inoculation process, a consortium of microalgae and bacteria was introduced into photobioreactors, constituting 20% of the volume, with an initial concentration of 28.645 mg/L.

Analytical procedure

Daily potential of hydrogen (pH) measurements were conducted in the experimental period using a pH meter (HANNA Instrument HI9813-6). All leachate samples were passed through centrifugation (TOMY LC-121) at 4000 rpm for 10 minutes for water quality analysis. Subsequently, the supernatant was collected to assess ammonia, nitrate, nitrite, phosphate, and COD concentrations using an ultraviolet-visible (UV-Vis) spectrophotometer (Shimadzu Spectrophotometer UV-1800). Ammonia concentration was quantified using the salicylate method (HACH Method 10031), with a measurement range spanning from 0.4 to 50 mg/L and a wavelength of 655 nanometers (nm). Nitrate concentration was measured with the cadmium reduction method (HACH Method 8029), comprising a range of 0.3 to 30 mg/L and wavelength at 500 nm. Furthermore, nitrite concentration was determined through the ferrous sulfate technique (HACH Method 8153), with method validity for concentrations ranging from 2 to 250 mg/L at a wavelength of 515 nm. For phosphate concentration, the estimation was in the range of 0 to 12.5 mg/L. The measurement protocol included transferring 5 mL of the supernatant into a 25 mL volumetric flask, which was then filled to the mark with mineral-free water. The measurement was conducted using the ultraviolet (UV) persulfate oxidation method, specifically following HACH Method 8007, at a wavelength of 880 nm. COD concentration assessments were accomplished using reactor digestion and calorimetry methods (HACH Method 8000), ranging from 20 to 1500 mg/L, with a wavelength of 620 nm. When the measured concentration surpasses or deviates from the required range, dilutions are performed on the supernatant, ensuring the concentration is consistent with the designated measurement range.

RESULTS AND DISCUSSION

The landfill leachate treatment plant in Blang Bintang, overseen by the Regional Waste Management Unit and spanning an area of 206 hectares (ha) in Aceh Besar District, has been in operation since 2014. In its initial implementation stage, the landfill was conceived to accommodate domestic solid wastes without the capacity for sorting or handling. These wastes were indiscriminately dumped without additional treatment, reflecting a lack of appropriate facilities. Despite recent efforts involving waste compaction and soil cover on the site, the landfill primarily receives waste from Banda Aceh and Aceh Besar District. On average, approximately 252 tons of household and commercial waste is generated daily, accumulating a total of 92.2 thousand tons of domestic waste in 2022. Table 1 presents an overview of the attributes pertaining to the solid waste deposited at Blang Bintang landfill for the entire duration of 2022. Among the various types of solid waste deposited, food waste constitutes the most considerable quantity and proportion, followed by wood trash. These waste types and proportions show similarities to the garbage composition data found in the study conducted by Qonitan *et al.* (2021) on other prominent cities in Indonesia. The data showed that food waste was the predominant material disposed of in landfills in various urban regions of the country. Farahdiba *et al.* (2023) also identified food waste, plastic, and wood as the primary sources of solid waste, significantly impacting landfill waste accumulation. Similarly, Ma *et al.* (2022) reported substantial food waste in landfills, considerably contributing to the increased concentration of organic compounds in leachate. Nanda and Berruti (2021) reported that waste type significantly influenced leachate quality, including age, geography, climate, and landfill management.

Landfill leachate characteristics

Earlier research has indicated that the characteristics and composition of landfill-generated leachate undergo changes based on maturity (Malovanyy *et al.*, 2022). Leachate from landfills is typically categorized into three age-related groups: young (<5 years), medium (5-10 years), and old (>10 years). When examining key pollution indicators for each age group, the average COD transitioned from over 15,000 mg/L in young landfills to below 3,000 mg/L in older counterparts. Ammonium nitrogen (NH_4-N) exhibited an increasing trend with landfill age, ranging from approximately 500-1,000 mg/L in young landfills to about 1,000-3,000 mg/L in older ones. While real-world measurements may vary from these averages, a discernible pattern of specific alterations emerges as leachates age. Analysis of BOD and COD measurements revealed a gradual decline in the concentration of organic pollutants in landfill leachate over time. Simultaneously, levels of

Table 1: Municipal solid waste composition in Blang Bintang landfill

Waste component	Composition (%)
Food waste	32.4
Wood	20.6
Paper and cardboard	3
Plastics	4.8
Metals	4.6
Textiles	6.8
Rubber	13.2
Glass	4.75
Others	9.85

Table 2: Comparison of landfill leachate characteristics of this study with other records

Parameters	Blang Bintang Aceh (this study)	Other parts of Indonesia[1]	Southeast Asia[2]
pH	7.95	7.6–8.5	7.4–8.46
Temperature (°C)	28.5	25.8–29.3	27.5–31
BOD (mg/L)	241	423–4,700	84–2,073
COD (mg/L)	4,177	143.5–4,000	590–2,920
NH_3 (mg/L)	1,708	0.196–11,324	7.5–850
NO_3 (mg/L)	625	3.7–638.8	3.2–20
NO_2 (mg/L)	27.5	0.117	22
PO_4 (mg/L)	14.97	3)	3)
Fe (mg/L)	14.82	0.6–1.8	1.447–12.81
Mn (mg/L)	5.94	0.4	0.001–0.3
Zn (mg/L)	9.7	0.06	0.2

1) Isnadina *et al*. (2019); Irfa'I *et al*. (2016); Yusmartini and Setiabudidaya (2013); Sukma and Widiadnyana (2020)
2) Xaypanya *et al*. (2018); Mohd-Salleh *et al.* (2020); Galarpe and Parilla (2012); Radzuan *et al*. (2005); Foul and Aziz (2009)
3) Data not available

NH_4-N and the pH of leachate tended to rise with the aging process. This suggests that as landfill leachate matures, there is a decrease in organic pollutants alongside an increase in ammonium levels and pH. In the current study, the analyzed leachate from the Blang Bintang landfill falls into the intermediate category within this aging classification. The relationship between leachate age and the BOD to COD ratio holds significant importance in evaluating the leachate's potential for biological treatment, as highlighted by Siracusa *et al*. (2020). Notably, the BOD to COD ratio tends to decrease as leachate ages, primarily due to the diminishing presence of biologically degradable organic components, as assessed by BOD. The observed decline in the BOD to COD ratio indicates a reduction in easily degradable organic matter over time, posing challenges for biological treatment methods. Understanding this intricate relationship is crucial for developing effective waste management strategies and refining leachate treatment procedures. Table 2 provides a comprehensive analysis of the characteristics exhibited by leachate obtained from the collection pond at the landfill leachate treatment plant within the Provincial Domestic Waste Management Unit in Blang Bintang, Aceh Besar Regency, Indonesia. This analysis is compared to leachate gathered from other locations in Indonesia and Southeast Asia. The leachate from the Blang Bintang landfill shares numerous similarities with leachate from other landfill sites across Indonesia and Southeast Asia, likely attributable to the shared tropical climate of these regions. Notably, the metal composition in the Blang Bintang leachate significantly differs from that of other areas, showing notably elevated levels of Zn, Mn, and Fe. This variation can be attributed to the heterogeneous composition of domestic solid waste at the Blang Bintang landfill, characterized by a lack of an adequate segregation mechanism. The COD and BOD concentrations in the treated leachate fell within the range observed in leachates from Indonesia and Southeast Asia.

The utilization of pond-based technology remains predominant in the landfill leachate treatment plant at the Provincial Domestic Waste Management Unit in Blang Bintang, Aceh. Initially, leachate from the landfill cell is collected and stored in a collection pond during the treatment process. The leachate characteristics presented in Table 2 are based on samples taken from this collection pond. Subsequently, the leachate undergoes treatment in an anaerobic pond to eliminate organic molecules. It is then directed to an anoxic pond with the primary objective of nitrogen removal, followed by transfer to an aeration pond to reduce concentrations of organic compounds and nitrogen. The final phase involves treatment within the stabilization pond. After undergoing a sequence of treatment steps, BOD and COD concentrations were measured at 117 mg/L and 350 mg/L, respectively. The concentrations of NH_3, NO_3 and NO_2 were recorded at 243 mg/L, 294 mg/L, and 337 mg/L, respectively. Initial concentrations of Fe, Mn, and Zn metals before leachate discharge into the aquatic environment were measured at 6.4 mg/L, 1.8 mg/L, and 6.8 mg/L, respectively. Despite the leachate undergoing previous biological processes before reaching the final pond, the BOD and COD levels had decreased, yet the BOD/

COD ratio indicated that their levels remained high. Even after getting the last pond, the BOD/COD ratio was greater than 0.5, suggesting that the leachate could undergo further biological treatment. Regarding the leachate effluent standard, the Government of Indonesia sets discharge into water bodies through the Minister of Environment and Forestry Regulation Number P.59/2016. The guidelines stipulate that treated leachate's maximum allowable COD and BOD are 300 mg/L and 150 mg/L, respectively. Although the leachate from Blang Bintang was essentially ready for discharge, COD and BOD were still four times higher than the allowable standard. While factors such as geographical location, climate, and waste composition can affect the leachate treatment process, the inability to meet the effluent standard highlights a weakness in the stabilization pond technology.

Distribution of microalgae and bacteria

The microalgae and bacteria in this study were meticulously identified through microscopic examination, utilizing a magnification of 400x. The comprehensive breakdown of the various types of microalgae and bacteria and their respective population sizes is presented in Table 3. Notably, a significant proportion of the identified bacteria belonged to the phylum cyanobacteria, characterized by their gram-negative characteristics. In contrast, the microalgae exhibited a broader taxonomic diversity, indicating a wider variety of microalgae species within the study sample. The most abundant bacteria identified in this experiment was *Centritractus belenophorus*. This bacterial type is characterized by its long and cylindrical shapes, featuring spines at both ends. The cell length and spine dimensions of *Centritractus belenophorus* ranged from 40-90 µm and 15-32 µm, respectively. Deže *et al*. (2020) explored the potential of microalgae and cyanobacteria communities as co-substrates for biogas production, with *Centritractus belenophorus* being one of the identified species in this community. The 42-day experiment yielded approximately 64% methane gas production from the microalgae and cyanobacteria community, with total biogas and volatile solid (VS) yields reaching 421.40 and 383.34 mL/g, respectively.

In this experiment, the second most abundant bacteria identified was *Gloeocapsa* sp., a member of the cyanobacteria phylum. Cyanobacteria have recently gained attention in the biomedical field due to their metabolites exhibiting antibacterial, antifungal, antiviral, anticancer, and antiplasmodial properties (Gacheva *et al*., 2013). Additionally, *Gloeocapsa* sp. is reported to have the potential to remediate heavy metals. Raungsomboon *et al*. (2008) reported that *Gloeocapsa* sp. can still grow at lead (II) (Pb^{2+}) concentrations of 0-20 mg/L, but the efficiency of Pb^{2+} metal removal decreases. At a low concentration of Pb^{2+} (2 mg/L), *Gloeocapsa* sp. can remove metal Pb^{2+} up to 100%. Besides lead (Pb) metal, *Gloeocapsa* sp. has been reported to remove other metals such as Zn, cadmium (Cd), and copper (Cu) (Pokrovsky *et al*., 2008). Another identified bacteria is *Microcystis* sp., which can produce the microcystin poison if it multiplies, potentially causing harm to plants and animals and making its presence in fresh waters less desirable. However, *Microcystis* sp. was reported to absorb nitrogen and phosphate (Xie *et al*., 2003). When it overgrows or blooms, *Microcystis* sp. can be used as a raw material for urea production, absorbing nitrogen and assimilating carbon from the environment (Krausfeldt *et al*., 2019). *Anabaena* sp., another type of bacteria identified in this experiment belonging

Table 3: Types and abundance of microalgae-bacteria consortium in leachate

Phylum	Genus	Species	Abundance (%)
Bacteria			
Ochrophyta	*Centritractus*	*Centritractus belenophorus*	28.14
Cyanobacteria	*Gloeocapsa*	*Gloeocapsa* sp.	25.97
Cyanobacteria	*Microcystis*	*Microcystis* sp.	24.24
Cyanobacteria	*Anabaena*	*Anabaena* sp	21.65
Microalgae			
Euglenazoa	*Euglena*	*Euglena sp.*	40.63
Cyanobacteria	*Spirulina*	*Spirulina sp.*	15.62
Bacillariophyta	*Synedra*	*Synedra acus*	14.38
Chlorophyta	*Closteriopsis*	*Closteriopsis longissima*	13.75
Ciliata	*Paramecium*	*Paramecium sp.*	12.5
Rotifera	*Trichocerca*	*Trichocerca sp.*	3.12

to cyanobacteria, has a cell size of about 6-10 µm. *Anabaena* sp. is known for its ability to fix nitrogen from the air and can potentially remove heavy metals. The biomass *Anabaena* sp. has been reported to remove up to 80% of Cd metal, with a maximum biosorption capacity of 162 mg Cd per gram of dry *Anabaena* sp. biomass (Clares *et al*., 2015). Additionally, *Anabaena* sp. has been reported to contribute to carbon dioxide removal (Chiang *et al*., 2011; Fernández *et al*., 2012). During the course of this study, *Euglena* sp. exhibited the highest prevalence among microalgae, followed by *Spirulina* sp., *Synedra acus*, *Closteriopsis longissima*, *Paramecium* sp., and *Trichocerca* sp., which were the subsequent most frequently identified species. *Euglena* sp. has garnered attention in the scientific community for its potential application in biofuel production, as highlighted in studies by Erfianti *et al.* (2023) and Indahsari *et al*. (2022). Additionally, *Euglena* sp. has demonstrated efficacy in reducing pollutants in wastewater, as supported by research conducted by Khatiwada *et al*. (2020) and Chiellini *et al*. (2020). In a study by Mahapatra and Chanakya (2013), *Euglena* sp. was investigated for cleaning domestic wastewater and generating biofuel, showing significant efficacy in removing 98% of ammonium and 92% of total organic carbon within eight days, with a substantial lipid content of 24.6% (w/w). The study underscores the potential of microalgae for dual purposes in wastewater treatment and biofuel production. *Spirulina* sp. was observed as the second most frequently occurring microalgae in this study, following *Euglena* sp. *Spirulina* species are acknowledged for their substantial protein content, as extensively documented by Khan *et al*. (2005). This high protein content makes *Spirulina* sp. suitable for human consumption, and studies by Jin *et al*. (2020), Mohadi *et al*. (2020), and Casazza *et al*. (2016) have highlighted its application as a dietary supplement for improving overall health. *Spirulina* sp. has also demonstrated resilience to and mitigation of the impacts of heavy metal pollution, further emphasizing its ecological importance and potential applications in industries and health-related fields.

Changes in the pH medium

Fig. 2 shows the variation in leachate pH during this experiment. The initial pH of the leachate in photobioreactors with and without CO_2 was 7.6 and 8.6, respectively. On the first day, the pH with the addition of CO_2 dropped to 7.1 but increased to 9.3 on the seventh day and was stabilized at the end of this experiment (9.379 ± 0.067). Meanwhile, the pH of the photobioreactor without CO_2 addition leachate tended to be stable from day 0 to day 20, which was around 9.28 ± 0.18. The pH of the medium is a factor affecting the growth of the microalgae-bacteria consortium (Khan *et al*., 2018). In this study, the identified microalgae-bacteria consortium had an optimum pH of 7-9. Changes in leachate pH in both photobioreactors were still in the optimum range for the microalgae-bacteria consortium. The most significant shift in pH occurred on the first day of the photobioreactor with the addition of CO_2 gas (Sutherland *et al*. 2014). This phenomenon was attributed to the occurrence of carbon fixation in the photosynthesis process,

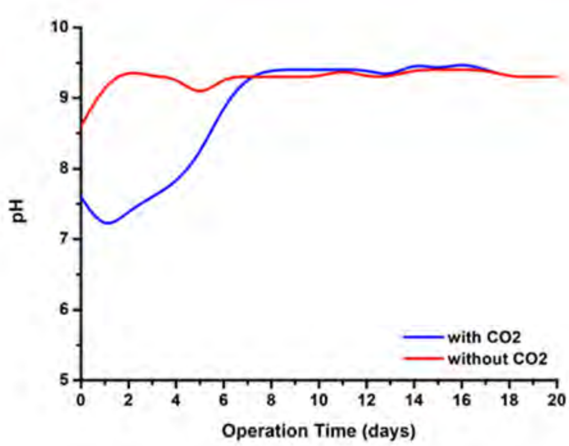

Fig. 2: Changes in the pH medium in the photobioreactor

facilitating the accumulation of OH^- ions in the medium (Shahid *et al*., 2020). The increase in pH in photobioreactors, attributed to the presence of CO_2, was controlled by the metabolic activity of microalgae. Sayadi *et al.* (2016) stated that an increase in pH value also showed a rise in microalgae growth. The observed elimination of pollutants in this investigation was not significantly affected by the variations in leachate pH, as shown in Figs. 3 and 4. Although there was an initial reduction in pH due to the addition of CO_2, the removal of COD, ammonia, nitrate, nitrite, and phosphates persisted. Both photobioreactors showed minimal variations in the reduction of pollutant concentrations due to a decrease in pH levels, which remained in the ideal range for the specific microalgae consortium found in this study. Consequently, the metabolic activity of microalgae persisted, facilitating the continuous elimination of pollutants in leachate.

Microalgae-bacteria consortium interaction in pollutant removal

The majority of microalgae applications for wastewater treatment focused on removing nitrogen and phosphorus compounds while generating biomass (Hernández-García *et al*., 2019). Microalgae require CO_2 for photosynthesis, and therefore, combining microalgae wastewater treatment with industrial CO_2 capture is common. However, if CO_2 levels are insufficient, additional CO_2 may be needed, resulting in higher costs. An alternative approach is the combination of microalgae with bacteria, requiring oxygen and producing CO_2 during metabolism that microalgae can supply through photosynthesis. This symbiotic microalgae-bacteria relationship offers excellent benefits for wastewater remediation. Each organism plays a distinct role in remediating wastewater in the microalgae-bacteria consortium. Bacteria contribute by enhancing the removal of organic carbon compounds, supplying vitamins and hormones that stimulate microalgal growth, and providing CO_2 to microalgae. Meanwhile, microalgae supply oxygen to bacteria, improve nitrogen and phosphorus elimination efficiency, and generate valuable biomass (Fallahi *et al*., 2021). The mechanism of wastewater pollutant removal relies on the symbiotic interaction between the microalgae and bacteria. Bacteria metabolize degradable organics and some nitrogen/phosphorus compounds, producing CO_2 and phytohormones that facilitate microalgal growth. Through photosynthesis, the microalgae consume the CO_2 and inorganic nutrients, generating oxygen for bacterial reuse and increased algal biomass. This microalgae-bacteria interplay forms resilient cell flocs able to withstand environmental disturbances (Jiang *et al*., 2021).

COD removal

Fig. 3 illustrates the reduction in COD concentration within the photobioreactor. The initial COD concentration in the leachate at the start of the experiment was measured at 233 mg/L. Throughout the investigation, the COD concentration in the photobioreactor displayed a consistent pattern, steadily decreasing. This trend was observed both in the presence and absence of CO_2, with final concentrations measured separately at 55 mg/L

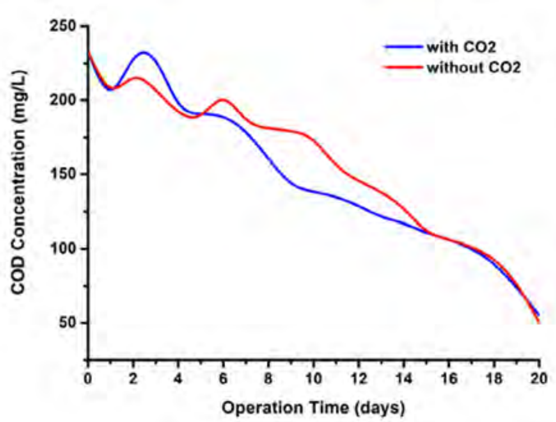

Fig. 3: COD elimination in the photobioreactors

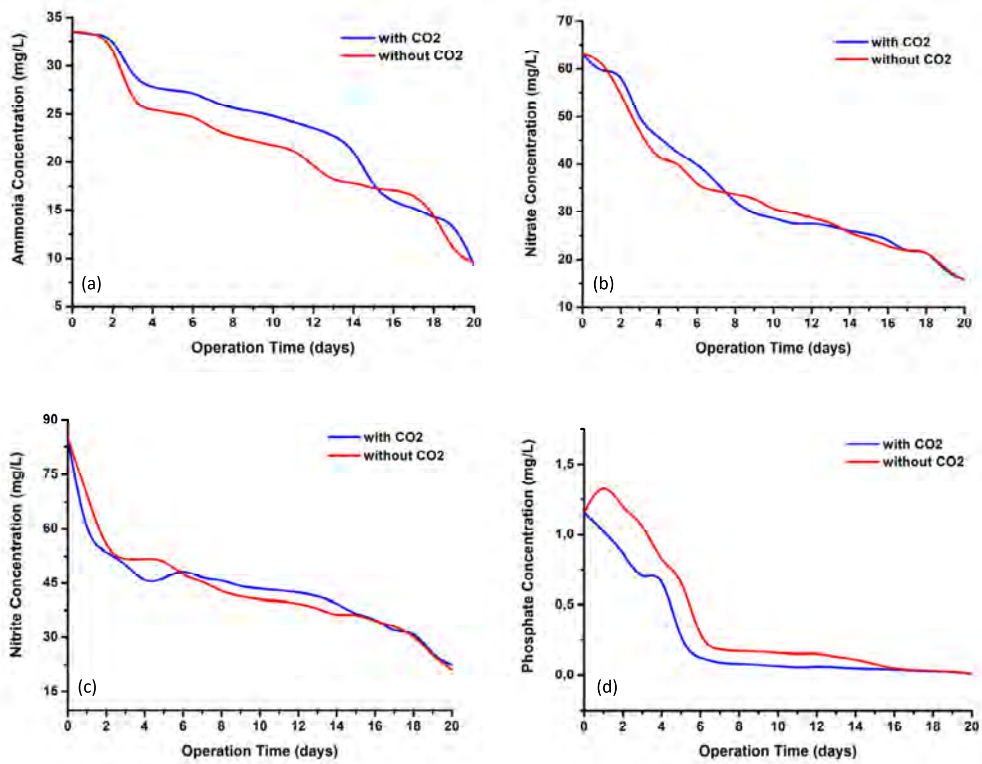

Fig. 4: Changes in (a) ammonia, (b) nitrate, (c) nitrite, and (d) phosphate concentration during the course of the experiment

and 50 mg/L. This observation aligns with the initial assumption made in this paper's introduction, suggesting that the microalgae and bacteria cultures cultivated in the leachate treatment pond possess resistance to the leachate's characteristics, facilitating a rapid acclimatization process. During the COD removal process, the concentration of the microalgae-bacteria consortium incubated in the photobioreactor increased. The initial consortium concentration at the start of the experiment was 28.645 mg/L. After 20 days, the concentrations reached 117.65 mg/L and 109.40 mg/L in the reactors with and without CO_2 addition, respectively. Consequently, to achieve approximately 75% COD removal, a minimum of 80.8 mg of microalgae-bacteria consortium per liter was required. This COD removal occurred through assimilation by the identified microalgae and bacteria species listed in Table 3. In comparison to previous studies, this study's 75% COD removal is comparable to the 77.14-81% efficiency reported by Tighiri and Erkut (2019), who also utilized a microalgae-bacteria consortium for leachate pollutant elimination. This consistency suggests that the COD removal results obtained here are in line with prior research using similar mixed microalgal-bacterial approaches for treating landfill leachate. In a recent laboratory study, Chang *et al*. (2023) tested a microalgae-bacteria consortium for treating dairy manure wastewater and achieved a COD elimination efficiency of 68.4 to 76.8% for organic matter removal. While slightly lower than the 75% COD removal obtained in this study, it further supports the reliable and promising capability of the microalgae-bacteria consortium in eliminating COD from various wastewater streams. In summary, this study contributes to the growing body of evidence showcasing the efficacy of the microalgae-bacteria consortium in COD removal from diverse wastewater sources.

The interaction between oxygen and carbon dioxide transfer within a microalgae-bacteria consortium is a crucial metabolic process. During this interaction, microalgae engage in photosynthesis, producing oxygen, which is then utilized by bacteria to oxidize organic compounds. Simultaneously, carbon dioxide is released as a by-product of bacterial metabolism, serving as the carbon source for microalgae (Oviedo *et al*., 2022). This collaborative interaction results in no significant difference in pollutant degradation performance between photobioreactors with and without CO_2 addition. This is because the carbon needs of microalgae are met through bacterial activity, marking a notable departure from photobioreactors relying solely on microalgae. The introduction of carbon dioxide in a system exclusively dependent on microalgae significantly influences their cultivation efficacy. Unlike microalgae-bacteria consortia, carbon supply in these systems depends on the culture medium and externally provided CO_2, as highlighted by Chaudhary et al. (2020) in their laboratory-scale study on *Chlorella vulgaris* in wastewater treatment photobioreactors supplied with either CO_2 (5% v/v) or regular air (0.03% CO_2 v/v). Their findings showed that photobioreactors with CO_2 addition achieved a 7% greater COD reduction and increased nitrogen removal rates by up to 16%. The microalgae-bacteria consortium has also been reported to reduce pollutant concentrations such as COD, ammonia, nitrate, nitrite, and phosphate (Fito and Alemu, 2019; Rossi *et al*., 2020). The results of this investigation demonstrate comparable COD removal outcomes between photobioreactors with and without CO_2 addition. Throughout the experiment, the COD concentration consistently decreased in both conditions, irrespective of the presence or absence of carbon dioxide. These findings align with the results reported by Thongpinyochai and Ritchie (2014), indicating a consistent and gradual decrease in COD levels over time. Thongpinyochai and Ritchie (2014) aimed to examine the potential of *Chlorella vulgaris*, a green microalgae species, in reducing COD concentrations in leachate. In the present experimental setting, *Chlorella vulgaris* achieved a COD elimination percentage of 51.05%, signifying its significant role in reducing COD levels within this specific environmental context.

Nitrogen and phosphate removal

Nitrogen removal in traditional sewage treatment relies heavily on the nitrification process, which requires oxygen. Mechanical aeration is commonly used to fulfill this oxygen requirement. However, implementing a microalgae-bacteria consortium can potentially reduce the need for substantial mechanical aeration. The microalgae consortium contributes by providing oxygen for nitrifying bacteria to carry out nutrient assimilation in wastewater, as demonstrated by Jia and Yuan (2016). Moreover, the nitrogen removal process within this consortium is not solely dependent on bacterial activity; it is also significantly influenced by the assimilation capacity of the microalgal biomass, as noted in the study by Oviedo *et al*. (2022). Fig. 4 illustrates the removal of nitrogen-phosphate compounds. The initial ammonia concentration in the photobioreactor was 29 mg/L. On the last day of the experiment, the photobioreactor's ammonia concentration with CO_2 and without CO_2 addition was 9.36 mg/L and 9.585 mg/L, respectively. The percentage of ammonia removal with the addition of CO_2 was more significant than that without CO_2, namely 72.09% and 71.42%, respectively. In comparison to the research conducted by Chang *et al*. (2023), the present study demonstrates a comparatively diminished efficacy in eliminating ammonia. Chang *et al*. (2023) documented a noteworthy achievement in the field of wastewater treatment, specifically in the context of dairy manure wastewater, with an ammonia removal efficiency reaching as high as 99%. The observed disparity underscores the significance of considering the intricacy and structure of the treatment system to achieve the most favorable outcomes in removing specific pollutants, such as ammonia, in wastewater treatment research. The initial concentration of nitrate was 63 mg/L, and there was no significant difference in nitrate and nitrite reduction between photobioreactors supplemented with and without CO_2 gas. The concentration of nitrate at the experiment's conclusion was 15.875 mg/L and 15.568 mg/L, respectively, for the photobioreactor with CO_2 and without CO_2, corresponding to the removal percentages of 74.86% and 75.35%, respectively. The initial concentration of nitrite in the photobioreactor was 85 mg/L. The removal of nitrite in the photobioreactor with and without the addition of CO_2 gas at the end of the experiment was 73.52% and 75.12%, respectively. At the start of the investigation, the phosphate concentration was 1.157 mg/L. Phosphate concentration decreased significantly on the seventh day in both photobioreactors. On the following days, the phosphate concentration continued to decline to 0.008 mg/L and 0.012 mg/L, respectively, for photobioreactors with added CO_2 and without CO_2, corresponding to the removal percentage of 99.29% and 98.94%, respectively.

The observed higher percentage of nitrate removal without the addition of CO_2 gas, as noted in this experiment, aligns with findings by Sutherland *et al*. (2014), who reported that the concentration of nitrate is lower without the addition of CO_2. The results of this experiment further corroborate the nitrogen-phosphate removal efficacy discussed by Olguin (2012), emphasizing the relatively high nitrogen removal rate exhibited by *Euglena* sp. It is essential to recognize that the efficiency of nitrogen and phosphorus removal can be influenced by various factors, including the composition of the medium and environmental conditions such as initial nutrient concentration, light intensity, nitrogen/phosphorus ratio, light/dark cycle, and algae species (Aslan and Kapdan, 2006). Based on this experiment's findings, it can be inferred that employing a consortium of microalgae and bacteria holds considerable potential as a viable and environmentally sound strategy for pre-treating leachate wastewater originating from a landfill in the Aceh region. However, it is imperative to acknowledge that the efficacy of employing a microalgae-bacteria consortium for leachate treatment could be contingent upon various elements, including the distinct attributes of the leachate, the configuration of the treatment system, and pertinent environmental restrictions in the given locality. Further research and initial inquiries may be needed to refine the process and ensure adherence to regulatory standards. In conclusion, this study's findings indicate that utilizing a consortium consisting of microalgae and bacteria exhibits promise as a feasible approach for the treatment of landfill leachate. This methodology demonstrates the ability to decrease operational expenses while effectively mitigating environmental issues related to landfill leachate.

Application of microalgae-bacteria consortium in landfill leachate treatment

Experimentally, using a microalgae-bacteria consortium demonstrated the successful removal of COD, ammonia, nitrate, nitrite, and phosphate from Blang Bintang landfill leachate. However, translating this technology into real-world applications for leachate treatment necessitates additional time and comprehensive investigations. Further testing is imperative, particularly in the areas of microalgae harvesting methods from leachate, assessment of microalgal lipid content cultivated on leachate, and the design of integrated treatment systems. While the application of microalgae-bacteria consortium promises to be efficient, effective, and economical, challenges must be addressed. Some bacteria exhibit parasitic tendencies towards microalgae, thereby diminishing both biomass quality and quantity. In the diverse microbiomes present in leachate, other organisms such as fungi, protozoa, or zooplankton may directly or indirectly inhibit microalgal growth, as highlighted by Jiang *et al*. (2021). A comprehensive and in-depth research approach is necessary to tackle these challenges. Furthermore, exploring the potential of harnessing microalgae consortium for biofuel production from leachate could significantly contribute to the sustainability of the treatment process. Although the microalgae-bacteria consortium exhibits promise for leachate treatment, the successful real-world application requires further optimization and a holistic understanding of the intricate dynamics involved. The ongoing research and refinement efforts are essential for realizing the full potential of this innovative approach in addressing the complex challenges posed by landfill leachate.

CONCLUSION

The effectiveness of pollutant degradation in landfill leachate was assessed through experimental investigations utilizing a consortium of microalgae and bacteria in two distinct photobioreactors, with and without the inclusion of CO_2 gas supplementation. The experimental results showcased the remarkable efficiency of the consortium consisting of microalgae and bacteria. The study's findings indicated a substantial decrease in COD by 75%, suggesting that the employed approach is highly effective in removing organic compounds from landfill leachate. Additionally, the consortium demonstrated significant efficacy in eliminating various nitrogen compounds, including ammonia, nitrate, and nitrite, with removal rates reaching as high as 75%. Remarkably, it also exhibited outstanding efficacy in eliminating phosphate compounds, achieving an impressive removal rate of 99%. One of the microalgae species identified in this study was *Euglena* sp., known for its remarkable ability to remove nitrogenous and phosphoric compounds. Surprisingly, regardless of the presence or absence of CO_2, the elimination of pollutants continued to exhibit a high level of efficacy, indicating that the inclusion of CO_2 did not substantially influence the overall pollutant removal process. Several factors may potentially elucidate the underlying causes for this occurrence. A mutually beneficial connection known as synergism is commonly observed in wastewater treatment processes incorporating microalgae and bacteria. Microalgae engage in photosynthesis, generating oxygen as a by-product, which becomes advantageous for bacteria relying on aerobic metabolic activities. Conversely, bacteria have the capacity to supply microalgae with organic carbon molecules, serving as nourishing sustenance. This symbiotic relationship allows for the recycling of carbon within the system. As these organisms undergo growth and reproduction, they progressively amass carbon within their biomass. The carbon can subsequently be extracted and utilized as a final product, such as biomass, for producing biofuels, mitigating the need for additional CO_2. Notably, the utilization of microalgae and bacteria in the wastewater treatment process capitalizes on their inherent capacity to metabolize carbon dioxide and the carbon compounds naturally present in the wastewater. This approach enhances the sustainability and environmental friendliness of the process by eliminating the requirement for an external source of CO_2 gas.

AUTHOR CONTRIBUTIONS

N. Emalya conceived, designed and conducted the experiment, sample collection and analytical measurements and prepared the manuscript draft. E. Munawar contributed to the design of the experiment and analytical measurements. Suhendrayatna supervised the first author, contributed to data analysis and examined the paper draft. Tarmizi supervised the first author and contributed to setting the experimental arrangements and data analysis. Y. Yunardi, the corresponding author, supervised the first author, conceived the research idea, designed the experiment, interpreted the results and finalized the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
µm	Micrometer
⁰C	Degrees Celsius
BG-11	Blue-green medium
BOD	Biological oxygen demand
Cd	Cadmium
cm	Centimeter
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Cu	Copper
Fe	Iron
ha	Hectare
Ind.	Individuals
Ind./L	Individuals per liter
L	Liter
L/min	Liter per minute
mg	Milligram
mg/L	Milligram per liter

mL	Milliliter
mL/g	Milliliter per gram
Mn	Manganese
NH_3	Ammonia
NH_4-N	Ammonium nitrogen
nm	Nanometer
NO_2	Nitrite
NO_3	Nitrate
Pb	Lead
Pb^{2+}	Lead (II)
pH	Potential of hydrogen
PO_4	Phosphate
rpm	Revolutions per minute
UV	Ultraviolet
UV-Vis	Ultraviolet-visible
VS	Volatile solid
v/v	Volume concentration
w/w	Weight concentration
Zn	Zinc

REFERENCES

Aditya, L.; Mahlia, T.M.I.; Nguyen, L.N.; Vu, H.P.; Nghiem, L.D., (2022). Microalgae-bacteria consortium for wastewater treatment and biomass production. Sci. Total Environ. 838: 1-13 **(13 pages)**.

Ahmed, A.T.; Alluqmani, A.E.; Shafiquzzaman, M., (2018). Impacts of landfill leachate on groundwater quality in desert climate regions. Int. J. Environ. Sci. Technol., 16(11): 6753-6762 **(10 pages).**

Amit; Nayak, J.K.; Ghosh, U.K., (2020). Microalgal remediation of anaerobic pre-treated pharmaceutical wastewater for sustainable biodiesel production and electricity generation. J. Water Process Eng., 35: 1-7 **(7 pages).**

Arun, S.; Sinharoy, A.; Pakshirajan, K.; Lens, P.N.L., (2020). Algae-based microbial fuel cells for wastewater treatment and recovery of value-added products. Renewable Sustainable Energy Rev., 132: 1-11 **(11 pages).**

Aslan, S.; Kapdan, I.K., (2006). Batch kinetics of nitrogen and phosphorus removal from synthetic wastewater by algae. Ecol. Eng., 28: 64-70 **(7 pages).**

Casazza, A.A.; Ferrari, P.F.; Aliakbarian, B.; Comotto, M.; Perego, P., (2016). Microalgae growth using winery wastewater for energetic and environmental purposes. Chem. Eng. Trans., 49: 565-570 **(6 pages)**.

Chang, Y.; Nagarajan,D.; Chen, J.; Chen, C.Y.; Wu, Y.; Whang, L.; Lee, D.; Chang, J., (2023). Microalgae-bacteria consortium for the treatment of raw dairy manure wastewater using a novel two-stage process: process optimisation and bacterial community analysis. Chem. Eng. J., 473: 1-14 **(14 pages)**.

Chaudhary, R.; Tong, Y.W.; Dikshit, A.K., (2020). Kinetic study of nutrients removal from municipal wastewater by *Chlorella vulgaris* in photobioreactor supplied with CO_2-enriched air. Environ. Technol., 41(5): 617-626 **(10 pages)**.

Chiang, C.L.; Lee, C.M.; Chen, P.C., (2011). Utilisation of the cyanobacteria *Anabaena* sp. CH1 in biological carbon dioxide mitigation processes. Bioresour. Technol., 102(9): 5400-5405 **(6 pages)**.

Chiellini, C.; Guglielminetti, L.; Pistelli, L.; Ciurli, A., (2020). Screening of trace metal elements for pollution tolerance of freshwater and marine microalgal strains: Overview and perspectives. Algal Res., 45: 1-13 **(13 pages)**.

Christensen, T.H.; Kjeldsen, P.; Bjerg, P.L.; Jensen, D.L.; Christensen, J.B.; Baun, A.; Albrechtsen, H.J.; Heron, G., (2001). Biogeochemistry of landfill leachate plumes. Appl. Geochem., 16: 659-718 **(60 pages)**.

Clares, M.E.; Guerrero, M.G.; García-González, M., (2015). Cadmium removal by *Anabaena* sp. ATCC 33047 immobilised in polyurethane foam. Int. J. Environ. Sci. Technol., 12(5): 1793-1798 **(6 pages)**.

Deže, D.; Mihaljević, M.; Kovačić, Đ.; Jovičić, D.; Kralik, D., (2020). Natural communities of microalgae and cyanobacteria from eutrophicated waters as potential co-substrates for small-scale biogas production. Appl. Biochem. Biotechnol., 192(3): 1016-1028 **(13 pages)**.

Effendi, H.; Kawaroe, M.; Lestari, D.F.; Mursalin; Permadi, T., (2016). Distribution of phytoplankton diversity and abundance in Mahakam Delta, East Kalimantan. Procedia Environ. Sci., 33: 496-504 **(9 pages)**.

Emalya, N.; Mairiza, L.; Bilqis, P.Z.; Suhendrayatna, S.; Munawar, E.; Yunardi, Y., (2023). Removal of organic and nitrogen compounds from domestic landfill leachate by microalgae. Biointerface Res. Appl. Chem., 13(2): 1-11 **(11 pages)**.

Erfianti, T.; Maghfiroh, K.Q.; Amelia, R.; Kurnianto, D.; Sadewo, B.R.; Marno, S.; Devi, I.; Dewayanto, N.; Budiman, A.; Suyono, E.A., (2023). Nitrogen sources affect the growth of local strain *Euglena* sp. isolated from Dieng Peatland, Central Java, Indonesia, and their potential as bio-avtur. IOP Conference Series: Earth Environ. Sci., 1151: 1-10 **(10 pages)**.

Fallahi, A.; Rezvani, F.; Asgharnejad, H.; Nazloo, E.K.; Hajinajaf, N.; Higgins, B., (2021). Interactions of microalgae-bacteria consortium for nutrient removal from wastewater: a review. Chemosphere. 272: 1-15 **(15 pages)**.

Farahdiba, A.U.; Warmadewanthi, I.D.A.A.; Fransiscus, Y.; Rosyidah, E.; Hermana, J.; Yuniarto, A., (2023). The present and proposed sustainable food waste treatment technology in Indonesia: a review. Environ. Technol. Innovation. 32: 1-16 **(16 pages)**.

Fernández, J.F.S.; González-López, C.V.; Fernández, F.G.A.; Sevilla, J.M.F.; Grima, E.M., (2012). Utilisation of *Anabaena* sp. in CO_2 removal processes: modelling of biomass, exopolysaccharides productivities and CO_2 fixation rate. Appl. Microbiol. Biotechnol., 94(3): 613-624 **(12 pages)**.

Fito, J.; Alemu, K., (2019). Microalgae–bacteria consortium treatment technology for municipal wastewater management. Nanotechnol. Environ. Eng., 4(1): 1-9 **(9 pages)**.

Foul, A.A.; Aziz, H.A., (2009). Primary treatment of anaerobic landfill leachate using activated carbon and limestone: batch and column studies. Int. J. Environ. Waste Manage., 4: 282-298 **(17 pages)**.

Gacheva, G.; Gigova, L.; Ivanova, N.; Iliev, I.; Toshkova, R.; Gardeva, E.; Kussovski, V.; Najdenski, H., (2013). Suboptimal growth temperatures enhance the biological activity of cultured cyanobacterium *Gloeocapsa* sp. J. Appl. Phycol., 25(1): 183-194 **(12 pages)**.

Galarpe, V.R.K.; Parilla, R.B., (2012). Influence of seasonal variation on the bio-physicochemical properties of leachate and groundwater in Cebu City sanitary landfill, Philippines. Int. J. Chem. Environ. Eng., 3: 175-181 **(7 pages)**.

Hernández-García, A.; Velásquez-Orta, S.B.; Novelo, E.; Yáñez-Noguez, I.; Monje-Ramírez, I.; Ledesma, M.T.O., (2019). Wastewater-leachate treatment by microalgae: biomass, carbohydrate and lipid production. Ecotoxicol. Environ. Saf., 174: 435-444 **(10 pages).**

Holt, J.G., (1994). Bergey's manual of determinative bacteriology, 9th. Ed. Lippincott Williams and Wilkins.

Indahsari, H.S.; Tassakka, A.C.M.A.R.; Dewi, E.N.; Yuwono, M.; Suyono, E.A., (2022). Effects of salinity and bioflocculation during *Euglena* sp. Harvest on the production of lipid, chlorophyll, and carotenoid with *Skeletonema* sp. as a bioflocculant. J. Pure Appl. Microbiol., 16(4): 2901-2911 **(11 pages)**.

Irfa'I; Yanuwiadi, B.; Suyadi., (2016). Landfills leachates quality and quantity in tidal area in Banjarmasin Landfills, Indonesia. Resour.

Environ., 6: 23-27 **(5 pages)**.

Isnadina, D.R.M.; Adi, M.P.; Ardiyanto, I., (2019). Technical evaluation of leachate treatment plant at Klotok Landfill Kediri in 2017. IOP Conference Series: Earth Environ. Sci., 245: 1-6 **(6 pages)**.

Jia, H.; Yuan, Q., (2016). Removal of nitrogen from wastewater using microalgae and microalgae–bacteria consortium. Cogent Environ. Sci., 2(1): 1-28 **(28 pages)**.

Jiang, L.; Li, Y.; Pei, H., (2021). Algal-bacterial consortium for bioproduct generation and wastewater treatment. Renewable Sustainable Energy Rev., 149: 1-15 **(15 pages)**.

Jin, S.E.; Lee, S.J.; Park, C.Y., (2020). Mass-production and biomarker-based characterisation of high-value *Spirulina* powder for nutritional supplements. Food Chem., 325: 1-6 **(6 pages)**.

Kamyab, H.; Friedler, F.; Klemes, J.J.; Cehlliapan, S.; Rezania, S., (2018). Bioenergy production and nutrients removal by green microalgae with cultivation from agro-wastewater palm oil mill effluent (POME) – a review. Chem. Eng. Trans., 70: 2197-2202 **(6 pages)**.

Khan, M.I.; Shin, J.H.; Kim, J.D., (2018). The promising future of microalgae: current status, challenges, and optimisation of a sustainable and renewable industry for biofuels, feed, and other products. Microb. Cell Fact., 17: 1-21 **(21 pages)**.

Khan, Z.; Bhadouria, P.; Bisen, P.S., (2005). Nutritional and therapeutic potential of *Spirulina*. Current Pharm. Biotechnol., 6(5): 373-379 **(7 pages)**.

Khatiwada, B.; Sunna, A.; Nevalainen, H., (2020). Molecular tools and applications of *Euglena gracilis*: from biorefineries to bioremediation. Biotechnol. Bioeng., 1-16 **(16 pages)**.

Krausfeldt, L.E.; Farmer, A.T.; Gonzalez, H.F.C.; Zepernick, B.N.; Campagna, S.R.; Wilhelm, S.W., (2019). Urea is both a carbon and nitrogen source for *Microcystis aeruginosa*: tracking 13C incorporation at bloom pH conditions. Front. Microbiol., 10: 1-12 **(12 pages)**.

Ma, S.;Zhou, C.;Pan, J.;Yang, G.; Sun, C.; Liu, Y.; Chen, X.; Zhao, Z., (2022). Leachate from municipal solid waste landfills in a global perspective: characteristics, influential factors and environmental risks. J. Cleaner Prod., 333: 1-10 **(10 pages)**.

Malovanyy, M.; Zhuk, V.; Tymchuk, I.; Grechanik, R.; Sereda, A.; Sliusar, V.; Marakhovska, A.; Vronska, N.; Kharlamova, O.; Heletiy, V., (2022). Efficiency of two-stage aerobic-reagent technology for the pre-treatment of different age leachates of municipal solid waste landfills. Case Stud. Chem. Environ. Eng.,6: 1-7 **(]7 pages)**.

Mahapatra, D.M.; Chanakya, H.N., (2013). *Euglena* sp. as a suitable source of lipids for potential use as biofuel and sustainable wastewater treatment. J. Appl. Phycol., 25: 855-865 **(11 pages)**.

Moejes, F.W.; Moejes, K.B., (2017). Algae for Africa: microalgae as a source of food, feed and fuel in Kenya. Afr. J. Biotechnol., 16(7): 288-301 **(14 pages)**.

Mohadi, R.; Hermansyah; Mavala, H.; Zulkifli, H., (2020). The effect of metal ion Cd(II) concentration on the growth of *Spirulina* sp. cultured on BG-11 medium. IOP Conference Series: Earth Environ. Sci., 530: 1-6 **(6 pages)**.

Mohd-Salleh, S.N.A.; Shaylinda, M.Z.N.; Othman, N.; Azizan, M.O.; Yashni, G.; Afnizan, W.M.W., (2020). Sustainability analysis on landfilling and evaluation of characteristics in landfill leachate: a case study. IOP Conference Series: Earth Environ. Sci., 736: 1-14 **(14 pages)**.

Munawar, E.; Fellner, J., (2013). Landfilling in tropical climates–measures for better design and operation. ISWA World Congr.: 1-14 **(14 pages)**.

Nanda, S.; Berruti, F., (2021). Municipal solid wastemanagement and landfill technologies: a review. Environ. Chem. Lett., 19(2): 1433-1456 **(24 pages)**.

Olguin, E.J., (2012). Dual purpose microalgae-bacteria-based systems that treat wastewater and produce biodiesel and chemical products within a biorefinery. Biotechnol. Adv., 30(5): 1031-1046 **(16 pages)**.

Oviedo, J.A.; Muñoz, R.; Donoso-Bravo, A.; Bernard, O.; Casagli, F.; Jeison, D., (2022). A half-century of research on microalgae-bacteria for wastewater treatment. Algal Res., 67: 1-16 **(16 pages)**.

Peng, Y., (2017). Perspectives on technology for landfill leachate treatment. Arabian J. Chem., 10: S2567-S2574 (**8 pages**).

Pokrovsky, O.S.; Martinez, R.E.; Golubev, S.V.; Kompantseva, E.I.; Shirokova, L.S., (2008). Adsorption of metals and protons on *Gloeocapsa* sp. cyanobacteria: A surface speciation approach. Appl. Geochem., 23(9): 2574-2588 **(15 pages)**.

Qonitan, F.D.; Suryawan, I.W.K.; Rahman, A., (2021). Overview of municipal solid waste generation and energy utilisation potential in major cities of Indonesia. J. Phys.: Conference Series, 1858: 1-9 **(9 pages)**.

Radzuan, N.Z.M.; Yaacob, W.Z.W.; Samsudin, A.R.; Rafek, A.G., (2005). Characteristics of leachate at the Air Hitam Sanitary Landfill in Puchong, Selangor. Geol. Soc. Malaysia Bull., 51: 41-46 **(6 pages)**.

Ratnawati, B.; Yani, M.; Suprihatin, Suprihatin; Hardjomidjojo, H., (2023). Waste processing techniques at the landfill site using the material flow analysis method. Global J. Environ. Sci. Manage., 9(1): 73-86 **(14 pages)**.

Raungsomboon, S.; Chidthaisong, A.; Bunnag, B.; Inthorn, D.; Harvey, N.W., (2008). Removal of lead (Pb^{2+}) by the cyanobacterium *Gloeocapsa* sp. Bioresour Technol., 99(13): 5650-5658 **(9 pages)**.

Richards, R.G.; Mullins, B.J., (2013). Using microalgae for combined lipid production and heavy metal removal from leachate. Ecol. Modell., 249: 59-67 **(9 pages)**.

Rossi, S.; Diez-Montero, R.; Rueda, E.; Cascino, F.C.; Parati, K.; Garcia, J.; Ficara, E., (2020). Free ammonia inhibition in microalgae and cyanobacteria grown in wastewaters: photo-respirometric evaluation and modelling. Bioresour. Technol., 305: 1-11 **(11 pages)**.

Samimi, M.; Shahriari Moghadam, M., (2018). Optimal conditions for the biological removal of ammonia from wastewater of a petrochemical plant using the response surface methodology. Global J. Environ. Sci. Manage., 4(3): 315-324 **(10 pages)**.

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages)**.

Sayadi, M.H.; Ahmadpour, N.; Capoorchali, M.F.; Rezaei, M.R., (2016). Removal of nitrate and phosphate from aqueous solutions by microalgae: an experimental study. Global J. Environ. Sci. Manage, 2(3):357-364 **(8 pages)**.

Shahid, A.; Malik, S.; Zhu, H.; Xu, J.; Nawaz, M.Z.; Nawaz, S.; Alam, M.A.; Mehmood, M.A., (2020). Cultivating microalgae in wastewater for biomass production, pollutant removal, and atmospheric carbon mitigation: a review. Sci. Total Environ., 704: 1-17 **(17 pages)**.

Siracusa, G.; Yuan, Q.; Chicca, I.; Bardi, A.; Spennati, F.; Becarelli, S.; Levin, D.B.; Munz, G.; Petroni, G.; Gregoria, S.D., (2020). Mycoremediation of old and intermediate landfill leachates with an Ascomycete fungal isolate, *Lambertella* sp. Water., 12(2): 1-16 **(16 pages)**.

Srimongkol, P.; Sangtanoo, P.; Songserm, P.; Watsuntorn, W.; Karnchanatat, A., (2022). Microalgae-based wastewater treatment for developing economic and environmental sustainability: current status and future prospects. Front. Bioeng. Biotechnol., 10: 1-18 **(18 pages)**.

Sukma, A.P.P.; Widiadnyana, W.M., (2020). Aspects influence leachate characteristics on leachate treatment plants in Temesi Landfill Gianyar Regency, Bali Province, Indonesia. E3S Web Conference. 148: 1-9 **(9 pages)**.

Sutherland, D.L.; Howard-Williams, C.; Turnbull, M.H.; Broady, P.A.; Craggs, R.J., (2014). Frequency of CO_2 supply affects wastewater microalgal photosynthesis, productivity and nutrient removal efficiency in mesocosms: implications for full-scale high rate algal ponds. J. Appl. Phycol., 27(5): 1901-1911 **(11 pages).**

Thongpinyochai, S.; Ritchie, R.J., (2014). Using *Chlorella vulgaris* to decrease the environmental effect of garbage dump leachates. J. Biorem. Biodegrad., 5(5): 1-12 **(12 pages)**.

Tighiri, H.O.; Erkurt, E.A., (2019). Biotreatment of landfill leachate by microalgae-bacteria consortium in sequencing batch mode and product utilisation. Bioresour. Technol., 286: 1-10 **(10 pages)**.

Xaypanya, P.; Takemura, J.; Chiemchaisri, C.; Seingheng, H.; Tanchuling, M., (2018). Characterisation of landfill leachates and sediments in major cities of Indochina Peninsula Countries—heavy metal partitioning in municipal solid waste leachate. Environ., 5(6): 1-24 **(24 pages)**.

Xie, L.; Xie, P.; Li, S.; Tang, H.; Liu, H., (2003). The low TN:TP ratio, a cause or a result of *Microcystis* blooms? Water Res., 37(9): 2073-2080 **(8 pages)**.

Yusmartini, E.S.; Setiabudidaya, D., (2013). Characteristics of leachate at Sukawinatan Landfill, Palembang, Indonesia. Conference Series: J. Phys 423: 1-5 **(5 pages)**.

Zaman, B.; Samadikun, B.P.; Budihardjo, M.A.; Hardyanti, N.; Rachma, A.F.; Hasna, S.I., (2020). Potential of phytotechnology in wastewater treatments to produce alternative electrical energy: a review. Conference Series: J. Phys.1524: 1-7 **(7 pages)**.

Zhu, S.; Qin, L.; Feng, P.; Shang, C.; Wang, Z.; Yuan, Z., (2019). Treatment of low C/N ratio wastewater and biomass production using co-culture of *Chlorella vulgaris* and activated sludge in a batch photobioreactor. Bioresour. Technol., 274: 313-320 **(8 pages)**.

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ORIGINAL RESEARCH PAPER

The effect of environmental awareness as a moderation on determinants of green product purchase intention

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aims to determine the effect of green brand positioning and knowledge and attitudes toward green brands on green product purchase intention moderated by environmental awareness. Collected data were from 230 Generation Y respondents in West Sumatra, Indonesia, who intended to purchase a low-cost green car. The achievement of this research is the implementation of environmental management policies in West Sumatra by increasing Generation Y awareness to buy green products to maintain the carrying capacity of the environment and encourage changes in environmentally conscious behavior.
METHODS: This study used a survey approach with a questionnaire. The population in this study is Generation Y in West Sumatra, who intend to buy low-cost green cars. This study used a nonprobability approach in the sample selection. A purposive sampling technique was applied, and data were analyzed using a structural equation model – the partial least squares method.
FINDINGS: There are five crucial findings in this study. First, green brand positioning has a significant effect on attitudes toward green brands, green product purchase intention, and green brand knowledge, which are 0.192, 0.151, and 0.680, respectively. Second, green brand knowledge has a significant effect on attitudes toward green brands and green product purchase intention, which are 0.271 and 0.229, respectively. Third, attitudes toward green brands have a significant effect on green product purchase intention of 0.067. Fourth, attitudes toward green brands mediate green brand positioning and knowledge on green product purchase intention by 0.218 and 0.057, respectively. Fifth, environmental awareness has a moderating effect between attitudes toward green brands and green product purchase intention at 0.161 but does not have a moderating effect between green brand positioning and green product purchase intention.
CONCLUSION: The findings of this study are for green marketers to supply high access levels to green product demand because consumers are increasingly aware of environmental preservation, and marketers must emphasize quality, price, and advertising to increase demand for green products. Moreover, the respondents were only taken from West Sumatra Province, so the study results cannot represent the entire country (Indonesia). Therefore, further research should attempt to expand the sample size to include more provinces in Indonesia. Finally, this study used a cross-sectional research design, which gathered data simultaneously.

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INTRODUCTION

The rapid development of globalization provides not only many advances in the lives of people but also many challenges to the environment, such as pollution and global warming (Aimon *et al.,* 2023; Kurniadi *et al.,* 2021; Samimi and Moghadam, 2024). These challenges will directly impact the sustainability of economic, social, and environmental development. Thus, environmental damage will attract the attention of all parties (Kolbadinezhad and Mahdiraji, 2021; Samimi *et al.,* 2023). In this case, it is important to protect the environment, such as increasing consumer purchasing behavior, which has an impact on the ecological environment (Aimon *et al.,* 2021; Kurniadi *et al.*, 2022). Zhuang *et al.* (2021) explained that consumer lifestyles have changed and are slowly leading to increased use of green products, and this will create opportunities for companies to focus on the green product market. For example, in the automotive industry, Honda, Toyota, and others have encouraged their brands to be green using green technology that protects raw minerals and reduces the greenhouse effect, especially in the manufacture of hybrid cars (half electric and half conventional) for environmental sustainability (Suki, 2016), and in Indonesia green cars are known as low-cost green cars (LCGC) (Komaladewi and Indika, 2017). Siyal *et al.* (2021) explained that the tendency of the public to buy LCGCs is quite high, including in West Sumatra, Indonesia, as evidenced by the increase in LCGC sales in the last 4 years. Therefore, it is important to expand a green business because it will help reduce waste costs, facilitate a healthy and safe work environment for employees, and ensure efficient and sustainable business operations (Mehraj and Qureshi, 2022; Yasir and Ali, 2021). There are many benefits offered by green businesses so an increasing number of companies will start implementing green production and marketing strategies in addition to fulfilling consumer tastes which have begun to change to gain business profits in the long term (Dangelico and Vocalelli, 2017; Sana, 2020). Although the demand and supply for green products have increased, the level of market expansion for green products is still inadequate because the level of purchasing green products is still low (Rex and Baumann, 2007). Enlarging the market for green products relies heavily on transforming consumer purchasing behavior (Zhuang *et al.,* 2021). Meanwhile, studying consumer behavior is difficult because it involves various factors (Darmawan *et al.,* 2021). Green consumer purchasing behavior is the result of the realization of green consumer purchasing intentions (Wang *et al.,* 2022). Previous researchers have conducted studies on the green product purchase intention (GPPI), and some researchers established that the GPPI is determined by various variables related to environmental insight. Chen and Chang (2012) discovered that green brand knowledge (GBK) was the main predictor that influenced the GPPI. Meanwhile, attitudes toward green brands (ATGB) have no positive effect on the GPPI. Furthermore, Himawan (2019) determined that green organizational image and environmental awareness (EA) positively and significantly influenced the GPPI. Then, Siyal (2021) confirmed that green brand positioning (GBP), ATGB, and EA had a positive and significant effect on GPPI. More in-depth research by Huang *et al.* (2014) showed that ATGB have a positive effect on the GPPI. Further research by Suki (2016) reported that GBP, ATGB, and GBK had a positive and significant effect on GPPI. Moreover, Tian *et al.* (2022) found that GBP, GBK, and ATGB influenced the GPPI. To add variety to this study and fill the gap that can be used as a decision-making tool, the novelty of this study is adding a mediating variable, namely, ATGB, and a moderating variable, namely, EA, which in previous research was still ignored. Exploring the factors that influence the GPPI of consumers is very useful for companies in creating marketing strategies (Siyal *et al.*, 2021). Additionally, it can build a good brand image, positive intentions, and a good value image in the eyes of the public (Sreen *et al.*, 2018). On the basis of empirical studies, many predictors influence the GPPI from the contexts of developed and developing countries (Candrianto *et al.,* 2023; Huang *et al.*, 2014; Mehraj and Qureshi, 2022; Suki, 2016; Siyal *et al.,* 2021; Wang *et al.,* 2022; Zhuang *et al.,* 2021). However, there is a lack of research on consumer perceptions of green behavior and strategies (Cronin *et al.,* 2011), and research focused on green brands is still rarely found (Chen, 2010). Hartmann *et al.* (2005) explained that consumer perspectives on GBP will have an impact on ATGB and research. Huang *et al.* (2014) explained that GBP influences ATGB and is a strong predictor of GPPI. Then, Mehraj and Qureshi (2022) combined the relationship between GBP on GPPI through knowledge and ATGB. Wang *et al.* (2022) explained that it is essential for companies to form a successful brand positioning because it is the main strategy for differentiation and increasing customer desire for the products offered. Moreover, several empirical studies tried to examine other predictors that have the potential to influence the GPPI; for example, studies by Zameer and Yasmeen (2022) reported that individuals who are EA will intend to consume environmentally friendly products. On the basis of empirical studies on GPPI, inconsistent results were still found; thus, providing an opportunity to reinvestigate this relationship, these empirical studies have not been comprehensive in exploring the GPPI, which is influenced by EA, GBP, GBK, and ATGB. Thus, further exploration should be carried out regarding GPPI from the consumer's perspective. In general, empirical studies position EA and ATGB as a predictor and a mediating variable, respectively. For this reason, this study complements previous studies by offering a moderating variable, namely, EA, to gain deeper knowledge regarding the relationship between GBP and green knowledge on GPPI through ATGB. Moreover, GPPI is more focused on the food industry, especially organic food, rather than the green automotive industry, such as cars with the LCGC concept. On the basis of the study contribution, this study determined the role of ATGB on the GPPI, which is driven by EA, GBP, and GBK.

Green product purchase intention

The GPPI refers to consumers' consumption of environmentally friendly products when consumers know the benefits of environmentally friendly products and have the will to protect the environment (Siyal, 2021). Then, the GPPI relates to different types of environmentally friendly behavior by individuals to give preference to green products compared with conventional products to express their desires (Mehraj and Qureshi, 2022). Consumers who are concerned about environmental problems will involve themselves in becoming a solution to the problem by changing their consumption patterns. When consumers are aware of the green attributes of a brand and then buy that brand, they are classified as green consumers because they are responsible for using their purchasing power to make changes (Situmorang, 2021).

Attitudes toward green products

Huang *et al.* (2014) defined customer preferences and the general assessment of green products as a representation of beliefs regarding green brands. ATGB are associated with overall customer preferences and brand evaluations that symbolize their favorability or unfavorability. Lee (2008) defines ATGB as a constructed term that builds on consumers' ratings and rational assessments of green brands. Moreover, ATGB is one's tendency to obtain green products (Almodareshhi, 2019). Furthermore, Kim *et al.* (2008) portrayed ATGB as a term derived from customer and logical judgments of the GPPI. Consumers can choose between brand alternatives due to a company's efforts to deliver eco-friendly products. Moreover, Naalchi (2019) discovered that ATGB favorably and significantly influences purchasing green products; thus, attitude is a representation of what customers prefer and do not prefer, and their purchase decisions are largely influenced by their ATGB (Kautish *et al.,* 2019).

Environmental awareness

EA is related to one's perspective and understanding of not only environmental concerns but also one's behavior. Therefore, consumers' use of green products is directed toward environmentally beneficial values and beliefs (Abd'Razackk *et al.,* 2017). Consumers with EA demonstrated it through their character and attitudes, as well as their strong loyalty and commitment to protecting the environment (Law *et al.,* 2017). EA is also a concept of balance, combining the environment, knowledge, values, and attitudes with emotional involvement toward environmental concern. It refers to psychological factors that measure individual desires for pro-environmental behavior. The term "green orientation," which is frequently used to describe environmentally conscious consumers, is expected to become more prevalent in the future. Consumers with high EA also choose green products, although the price is higher. During critical environmental conditions, environmental sustainability awareness becomes higher. This pressure has caused a change in the behavior of people who are concerned about the environment. Consumers sensitive to a product's technological attributes are called green consumers. Therefore, EA can influence the consumer's ATGB (Chen, 2009).

Green brand positioning

The green positioning of a company is an important part of the overall plan to provide a framework for the organization that is both emotional and functional (Situmorang *et al.,* 2021). Furthermore, Suki (2016) defined GBP as designing an offer and promoting the brand features of a firm that set it apart from its rivals through green brand attributes. According to White *et al.* (2019), consumers with a commitment to environmental protection and positive experiences with green products have a higher tendency to GPPI. Baiquni and Ishak (2019) explained that brand positioning could be used to gain a company's competitive advantage. Additionally, GBP emphasizes how a firm's communications and qualities are differentiated from its rivals as a consequence of the inclusión of ecologically friendly attributes. Hence, GBP is essential for positioning the brand in the minds of consumers so that companies can survive in the market for green products. This is because green consumers with great GPPI items and product information are more likely to make repeated purchases as a result of brand positioning. Moreover, Hartmann *et al.* (2005) characterized GBP as the worth or qualities that a green brand can deliver, which has important meaning for consumers. Similarly, Suki (2016) explained that GBP is about how companies use green images to represent themselves to be perceived by the customer market. Further, according to Hilmawan (2019), GBP is associated with the worth of eco-friendly goods and services determined by a company's environmentally friendly attributes thatare considered important by its target market. Ultimately, GBP is the action of devising offerings and promotions for a new image of the business to set a brand apart from its rivals with green brand attributes (Huang *et al.,* 2014).

Green brand knowledge

GBK, according to Suki (2016), is the way organizations convey understanding or details about the distinctiveness of their goods within their brand attributes. It concerns the promises that the organization makes to its customers and the environment. It is confirmed by Zhou *et al.* (2020); it would affect their intention to purchase them. Therefore, companies must be able to assure customers of the risks associated with using products made from chemicals and the importance of using healthy and green products so that consumers are aware of what the organization has to offer (Hilmawan, 2019). Villagra *et al.* (2022) also defined GBK as identifying the characteristics and attributes of green products, which include brand image and trust. It contrasts with green knowledge, which reflects consumers' general level of EA (Lin *et al.*, 2017). Thus, GBK captures consumer-specific awareness that draws on the brand's commitment and concern for the environment. Law *et al.* (2017) stated that brand knowledge can measure customers' familiarity with a brand. Furthermore, according to Siyal (2021), GBK provides knowledge that alters behavior among consumers by increasing green product awareness. Meanwhile, as Law *et al.* (2017) asserted, GBK refers to two terms: (1) brand awareness is the strength of a brand's nodes in a consumer's memory and (2) brand image is a unique, strong, and profitable brand association in the memories of consumers. Additionally, an understanding of a product's distinctive green brand characteristics and advantages for health and environmental preservation is provided. Customers always expect and prefer to learn more about green brands, broaden their awareness of environmental concerns, and make purchasing environmentally friendly products simpler (Woo and Kim, 2019). Hence, GBK is a high level of knowledge about environmental protection owned by consumers and impacts the consumption of green products (Huang *et al.,* 2014).

MATERIALS AND METHODS

Hypothesis development of GBP and ATGB

According to several studies, a greater awareness of customer environmental knowledge is linked to favorable opinions toward green brands (Kang and Hur, 2012; Kauatish *et al.,* 2019). Abd'Razack *et al.* (2017) claimed that GBP can positively influence the consumer's ATGB. Similarly, Huang *et al.* (2014), Lin *et al.* (2017), and Suki (2016) supported the previous research results that GBP has a favorable influence on the consumer's ATGB. Several studies have also revealed that GBP significantly and positively influenced ATGB (Mehraj and Qureshi, 2022; Situmorang, 2021).

H1: GBP affects ATGB.

Hypothesis development of GBP and intention to GPP

GBP is a vital indicator for assessing consumer purchasing interest in green products (Suki, 2016). Consumers who have felt the impact of using green products of a company due to their knowledge of green brands will continue to increase their purchasing intensity for the products due to the green brand attributes campaigned by the company (Siyal et al., 2021; Mehraj and Qureshi, 2022). Additionally, GBP is important for positioning the brand in the minds of consumers so that companies can survive in the market for green products (Lin and Chang, 2012). Previous researchers have also supported research results that GBP greatly influences the propensity to GPPI (Huang *et al.,* 2014).

H2: GBP affects the intention to GPPI.

Hypothesis development of GBP and GBK

Green positioning strategies primarily build brand associations by conveying an understanding of eco-product attributes (Rios *et al.,* 2006). Marketing communications may be used to perform the strategy for GBP that forms positive perceptions in the minds of consumers. GBK also provides data that alter customer behavior by increasing green product awareness (Siyal, 2021). This positive perception improves GBK through rand awareness. Many studies have discovered that GBP can influence GBK (Huang, 2014; Mehraj and Qurashi, 2022).

H3: GBP affects GBK.

Hypothesis development of GBK and ATGB

Consumers who have complete information about brands with a commitment to the environment will be able to generate feelings of liking or disliking the brand (Situmorang *et al.*, 2021). Some researchers have revealed that consumers develop a high environmental commitment due to their high ATGB (Braun *et al.,* 2018; Mostafa, 2007). Furthermore, Mehraj and Qurashi (2022) argued that companies' environmentally friendly brand attributes would lead to the consumer's ATGB (Huang *et al.,* 2014; Suki, 2016; Wang *et al.*, 2022).

H4: GBK affects ATGB.

Hypothesis development of GBK and intention to GPPI

GBK informs consumers about an item's distinctive brand characteristics and overall environmental advantages. Consumers with knowledge about eco-products will tend to enhance their intention to buy in the future (Smith and Paladino, 2010). Consumers also expect to learn more about green brands, broaden their awareness of environmental concerns, and make it simpler for them to buy eco-products. Several investigations have proven that customer intentions and actual GPPI are favorably impacted by environmental education (Chen and Chang, 2012; Suki, 2016). On the basis of previous research, this study proposes the following hypothesis:

H5: GBK affects the GPPI.

Hypothesis development of ATGB

Several research results report that when consumers have higher ATGB, they tend to develop intentions to GPPI. Moreover, several studies on green consumer behavior have revealed that favorable customer ATGB impacted GPPI (Huang *et al.,* 2017; Kautish *et al.*, 2019; Wang *et al.*, 2022). Similar results were also found by Suki (2016) and Paul *et al.* (2016) that consumer preference for eco-products increases the intensity of purchasing eco-products. Similarly, Siyal *et al.* (2021) uncovered a favorable relationship between ATGB and green buying intentions. Other studies have also revealed that favorable customer ATGB affected the GPPI (Kautish *et al.,* 2019; Wang *et al.*, 2022). Moreover, Naalchi (2019) discovered that ATGB positively and significantly influences purchasing green products.

H6: ATGB affects the intention to GPPI.

H7: ATGB mediates the relationship between GBP and the GPPI.

H8: ATGB mediates the relationship between GBK and the GPPI.

Hypothesis development of EA

EA is a concept of balance, combining the environment, knowledge, values, and attitudes with emotional involvement toward environmental concern. It is also an individual belief element that guides the customer to conduct environmentally beneficial purchasing behavior (Abd'Razack *et al.,* 2017). It refers to psychological factors that measure individual desires for pro-environmental behavior (Zelezny and Schultz, 2000). Environmentally conscious consumers are sometimes referred to as having a "green orientation," and this trend is expected to continue. Customers who care deeply about the environment will also choose green items although the price is higher. In the current critical environmental conditions, environmental sustainability awareness is becoming increasingly high. This pressure has caused a change in the behavior of people who are concerned about the environment. Consumers sensitive to a

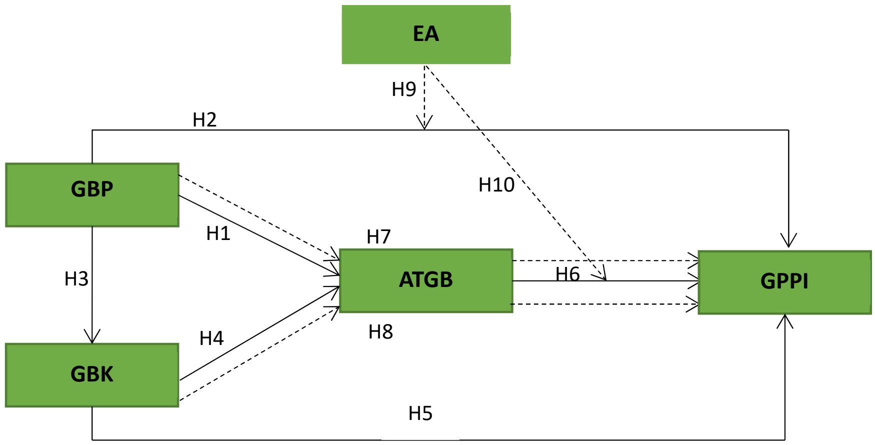

Fig. 1: Research Framework

product's technological attributes are called green consumers. EA moderates the relationship between GBP and GPPI through consumer awareness of the environment to change their purchasing behavior by increasing the intensity of using green products after knowing the benefits they feel, so that in the end it can increase the GPPI. Furthermore, EA moderated the relationship between ATGB and GPPI through pressure from increasingly critical environmental conditions, so that awareness among the community regarding environmental sustainability became increasingly high. This pressure has caused a change in people's behavior to become concerned about the environment, which will increase the intensity of the use of products that are oriented toward environmental sustainability. Before consuming green products, a consumer must have an attitude as an overall evaluation of the green brand. Therefore, the following hypotheses are proposed:

H9: EA moderates the effect of GBP on the GPPI.

H10: EA moderates the effect of ATGB on the GPPI.

On the basis of the theoretical basis and research hypothesis, the model of this study is proposed (Fig. 1).

Data collection

This study applies a survey method using a questionnaire as a research instrument. In distributing questionnaires, respondents are asked to provide responses or answers by selecting one of the answer options provided to be crossed. The respondents' answers given are still qualitative but will be quantified and measured using a Likert scale. The preparation of instruments in this study is based on variable indicators. The determination of these indicators is based on a grid that has been created first. The preparation of questionnaire items or statements considers the ease of filling in by respondents. The population in this study was Generation Y, who first desired to purchase LCGC. The criteria for this study sample were (a) people who lived in West Sumatra, (b) did not yet have an LCGC, (c) already had jobs and adequate income, and (d) had completed a minimum education level of senior high school or equivalent. In this study, a nonprobability sample was used because the researcher did not obtain the detailed identities of the respondents needed to create the sampling frame. The sampling technique is conducted purposively, namely, a sampling technique with certain criteria or considerations. The formula proposed by Hair *et al.* (2021) was used to discover the sample size. Hair's formula was used because the population size was uncertain and the formula suggests that the minimum sample size is 5–10 times the variable indicator (Hair *et al.,* 2021). Therefore, the 23 indicators (Table 2) were multiplied by 10, obtaining a sample size of 230 (23 × 10) = 230. According to the data in Table 1, the distribution of the number and percentage of respondents is as follows. There were 139 (63.18 percent: %) and 81 (36.81%) male and female respondents, respectively.

Table 1: Characteristics of respondents

No	Featured characteristics		Achievements	
			Frequency	%
1	Gender	Male	139	63.18
		Female	81	36.81
2	Age (years)	26–30	73	33.18
		31–36	86	39.03
		37–41	61	27.72
3	Occupation	Civil servants	84	38.18
		Private employees	76	34.54
		Self-employed	50	22.72
4	Income (USD)	200–300	18	8.18
		301–400	15	6.81
		401–500	57	25.90
		>500	76	34.54

Variable types and measurement indicators

Variable	Measurement items	Source
GBP	Five items	Huang *et al.*, 2014
GBK	Five items	Zhou *et al.*, 2020
ATGB	Four items	Huang *et al.*, 2014
EA	Six items	Zhou *et al.*, 2020
GPPI	Three items	Huang *et al.*, 2014

This indicates that male respondents are more inclined to participate in providing the valuation of the intention to purchase an LCGC. Respondents aged 31–36 years and with civil servant professions were more inclined to participate in providing the valuation of the intention to purchase LCGC. The number of respondents who earned IDR 200-300 USD was 18 (8.18%). 15 earned IDR 301-400 USD (6.81%). 57 Earned IDR 401-500 USD (25.90%). And 76 earned more than 500 USD (34.54%). This denotes that respondents who earned more than 500 USD were more inclined to participate in providing the valuation of the intention to purchase an LCGC.

Measurement

On the basis of the scale used in this study, 23 indicators were used to measure the five variables identified. The indicators used in this study were taken from previous research and are presented in Table 2.

Data analysis

Structural equation modeling (SEM), a multivariate analysis used to explain a simultaneous linear connection between observational variables (indicators) and factors that could not be assessed directly, was the data analysis method applied in this research. Then, the partial least squares (PLS) component-based SEM method was applied. Its objective was to evaluate structural models and measurements. The PLS is favorable because it applies nominal, ordinal, and interval scale variables and places fewer expectations on the data distribution. Additionally, it works best for forecasting a group of dependent variables from a large range of independent variables and is preferable for identifying group differences when the data are not normally distributed (Hair, 2021).

RESULTS AND DISCUSSION

Outer loading

The loading factor was the subject of the initial examination and demonstrated how indicators and their hidden variables interacted. When the loading value (λ) is <0.7, reflective indicators must be removed from the measurement model. The model is recalculated if theloading value (λ) is <0.7, which is a valid indicator. High-factor loading indicators make a significant contribution to the explanation of latent variables. Conversely, indicators with low factor loading are weak in explaining latent variables. If the loadingvalue (λ) for the variance inflation factor is <5, there is no multicollinearity concern. Further, the average variance extracted (AVE) values of the

Table 3: Measurement results

Indicator	Loadingfactor	Composite reliability	AVE	Cronbrach'salpha
GBP		0.853	0.618	0.743
High-tech LCGC	0.817			
LCGCs produce low air pollution	0.786			
LCGCs are more advanced than other types of cars	0.861			
LCGCs are more creative than other types of cars	0.853			
GBK		0.853	0.630	0.852
Finding out environmental information related to LCGCs	0.817			
LCGCs have a good reputation	0.886			
LCGCs can be trusted about their promise to the environment	0.855			
LCGCs is professional in maintaining its environmental Reputation	0.876			
ATGB		0.893	0.475	0.620
LCGCs are more reliable than diesel-fueled cars	0.643			
LCGCs can represent economic status	0.782			
LCGCs fill the need	0.793			
EA		0.909	0.535	0.825
Choosing products that do not damage the environment although they are expensive	0.623			
Refusing to purchase products that can damage the environment	0.626			
Purchasing eco-labeled products even though they are more expensive	0.724			
Sorting recyclable waste at home	0.749			
Conscious of actions to improve the environment	0.824			
Often paying attention to and absorbing knowledge and information about the environment	0.818			
GPPI		0.778	0.661	0.743
Bought an LCGC to save fuel	0.761			
Bought an LCGC out of concern for the environment	0.907			
The probability of purchasing an LCGC is high	0.761			

variables are above the minimum value of 0.5. Table 3 provides a summary of the outcomes.

The constructs' discriminant validity was evaluated. Convergent validity was tested using the following three criteria: (1) all loading factors must be exceeding 0.60; (2) the composite reliability must be upper than 0.70; and (3) the AVE must be exceeding 0.50. Furthermore, all Cronbach's alpha values for each measurement were higher than 0.70, signifying strong measurement reliability. The square root of the AVE for each construct (i.e., the diagonal entry for each column) was larger than its association with other constructs, indicating that all of the constructs had sufficient discriminant validity (Shaykh-Baygloo, 2021).

Discriminant validity

The level of discriminant validity illustrates how certain constructs within the same model are different. Several discriminant validity tests are available, including the Fornell and Larcker criteria, cross-loading, and heterotrait–monotrait (HTMT) ratio. This study used HTMT analysis because all HTMT ratios are below the maximum threshold of 0.85, demonstrating the superiority of HTMT analysis over other techniques for determining discriminant validity. Therefore, this study used the HTMT analysis in evaluating discriminant validity, which is concluded in Table 4.

Table 5 presents the result of the hypotheses testing. This study discovered that GBP influenced ATGB ($\beta = 0.015$, $p < 0.015$), GBP affected the GPPI ($\beta = 0.151$, $p < 0.019$) and GBK ($\beta = 0.680$, $p < 0.000$), and GBK affected ATGB ($\beta = 0.271$, $p < 0.001$). Similarly, the GPPI items were influenced by green brand awareness ($\beta = 0.229$, $p < 0.001$). In addition

Table 4: Discriminant validity results

Variable	EC	GPI	GBK	GBP	AGB
EA					
GPPI	0.702				
GBK	0.465	0.692			
GBP	0.402	0.576	0.761		
ATGB	0.405	0.661	0.577	0.548	

Table 5: Direct, mediation, and moderation effects on variables

H	Hypothesis	B	p-value	Decision
H1	GBP influences ATGB	0.192	0.015	Accepted
H2	GBP influences GPPI	0.151	0.019	Accepted
H3	GBP influences GBK	0.680	0.000	Accepted
H4	GBK influences ATGB	0.271	0.000	Accepted
H5	GBK influences GPPI	0.229	0.001	Accepted
H6	ATGB influence GPPI	0.067	0.002	Accepted
H7	ATGB mediate GBP and GPPI	0.218	0.000	Accepted
H8	ATGB mediate GBK and GPPI	0.057	0.000	Accepted
H9	EA does not moderate the effect of GBP on GPPI	0.034	0.470	Rejected
H10	EA moderates the effect of ATGB on GPPI	0.161	0.001	Accepted

to examining the direct effects of the GBP, GBK, ATGB, and GPPI, this study investigated the indirect effects of ATGB on GBP and GBK on the GPPI. It was discovered that ATGB mediated the effect of GBP on the GPPI ($\beta = 0.128$ $p < 0.000$) and mediated GBK on the GPPI ($\beta = 0.057$ $p < 0.000$). Additionally, this study discovered that EA did not moderate the effect of GBP on the GPPI ($\beta = 0.034$ $p > 0.470$) but moderated the effect of ATGB on the GPPI ($\beta = 0.161$, $p < 0.001$).

This study examined the effects of GBP, GBK, and ATGB on the GPPI. Furthermore, the effect of GBP on GBK was also tested. Finally, the mediating effect of ATGB and the moderating effect of EA were also investigated. First, this study proves that the GBP has a positive and significant effect on ATGB. These results reveal that the brand attributes and environmentally friendly values that are campaigned by companies increase consumer preferences for environmentally friendly products. Given the brand identity and the power of environmentally friendly company negotiations are equally influenced by GBP, it is very logical if the brand is actively communicated to potential consumers. The results of this study are in line with those of Zhuang *et al.* (2021) showing that companies capable of positioning their brands in the minds of consumers to the environmental benefits of the company will ultimately be able to reflect consumer preferences and the overall evaluation of GBP. Second, this study proves that the GBP has a positive and significant effect on the GPPI. These results reveal that the GPPI will increase through the company's role in positioning the environmental benefits of their brand to consumers. Consumers who feel the impact of the use of environmentally friendly products because of their knowledge of GBP will continue to increase the number of their purchases of environmentally friendly products because of the environmentally friendly brand attributes campaigned by the company. The results of this study are in line with those of Mehraj and Qureshi (2022) showing that GBP reacts as one of the important strategies that will have an impact on GPPI, which good GBP means consumers are aware and care to buy green products. Additionally, green marketers must emphasize the quality, price, advertising, and environmentally friendly products for consumers to buy green products. Third, this study proves that the GBP has a positive and significant effect on GBK. These results reveal that the GBP strategy through a proactive communication campaign increases GBK in the form of environmentally friendly brand awareness and image and provides opinions that are preferred by customers to environmentally friendly companies. Companies that have an environmentally friendly brand in their portfolio must conduct environmentally friendly marketing to increase brand awareness. To increase awareness, companies can express details about their brand's environmental problems. The results of this study are in line with those of Siyal *et al.* (2021) showing that GBP is the concept of providing information that changes consumer behavior to be more informed about environmentally friendly products, which this condition will produce positive perceptions of better GBK through brand awareness. Fourth, this study proves that GBK is positive and significantly correlated to ATGB. These results reveal that consumers with complete information about environmentally friendly products have positive ATGB. The GBK attributes offered by the company can ultimately lead to consumer attitudes and preferences toward a brand. Furthermore, the high commitment of consumers to the environment is caused by the high ATGB. The results of this study are in line with those of Huang *et al.* (2014) showing that companies that can provide the uniqueness of the GBK about the promise given by the environmental commitment will be able to reflect the choice of consumers and overall evaluation of the GBK. Fifth, this study proves that the GBK correlates positively and significantly with GPPI. These results reveal that a better pro-environmental attitude and greater consumption intentions toward GPPI are largely determined by the higher level of consumer environmental knowledge. Consumers hope to receive reliable information about environmental problems to improve their GBK to facilitate GPPI. The results of this study are in line with those of Suki (2016) showing that GBK is the strongest predictor for GPPI; therefore, companies must consider green products as a profitable investment in the long run and ensure that the performance of the green product environment must meet consumer expectations. Sixth, this study proves that ATGB is positively and significantly correlated with GPPI. These results reveal that when consumers' ATGB is increasingly preferred, the consumer's GPPI level will also increase. Reliability, dependability, and trust are the inferential components of an environmentally friendly brand. GPPI's actions show that customers care about the environment through ATGB. A positive brand attitude shows that consumers have high EA by taking pro-environmental actions so that they mentally see opportunities to adopt a brand. The results of this study are in line with those of Zavali and Theodoropoulou (2018) showing that customers with favorable ATGB tend to maintain a more affirmative behavior and have greater intentions toward GPPI because their GPPI assessments are often based on ATGB. Seventh, this study proves that ATGB mediates GBP and GPPI. These results reveal that when consumers become environmentally friendly, they develop positive ATGB. If their ATGB is very positive, they will most likely develop GPPI. GBP is an effort made to emphasize the memory of consumers that the products produced by the company do pay attention to environmental aspects. Meanwhile, ATGB is explained as a term derived from customer and logical assessments from the GPPI. For a company to emphasize its position as an environmentally friendly product, it will influence consumer intentions regarding the GPPI. The results of this study are in line with those of Huang *et al.* (2014) showing that ATGB is crucial in forming GPPI. Customers who are deeply committed to supporting environmentally friendly products will develop a strong desire to purchase them. Eighth, this study proves that ATGB mediates GBK and the GPPI. These results reveal that the GBK strategy conveyed through marketing communications can increase the GPPI. However, sometimes purchase intentions arise after consumers' judge whether the product is good or not for consumption, so ATGB will increase intentions for the GPPI. The results of this study are in line with those of Mehraj and Qureshi (2022) showing that consumers with broader knowledge will develop a more positive ATGB attitude, thereby increasing the quantity of GPPI because GBK influences ATGB which in turn will influence GPPI. Ninth, this study proves that EA cannot moderate the relationship between GBP and GPPI. These results reveal that although consumers support environmental conservation efforts, their EA cannot increase the quantity of GPPI despite the company's communication efforts. This happens because the cost of environmentally friendly products is greater, thereby reducing consumers' interest in environmentally friendly products even though they are aware of the perceived benefits. The results of this study contradict those of Leaniz *et al.* (2017) showing that consumers with strong EA and higher GBP tend to indicate they better understand the environmental protection aspects of GBP. After purchasing GBP, these messages are immediately transferred to consumers, making them feel EA even more. Tenth, EA can moderate the relationship between ATGB and GPPI. These results reveal that consumers who have higher EA prefer GPPI if they feel that their purchasing decisions can have a positive impact on the environment and thus prefer to be responsible for it. This pressure causes changes in people's behavior toward the environment, increasing the quantity of GPPI. The results of this study are in line with those of Kautish *et al.* (2019) showing that in increasingly critical environmental conditions, EA will increase.

CONCLUSIONS

An important conclusion in the research highlighting its novelty is that EA is not needed to see the influence between GBP and GPPI because the p-value of 0.470 is large from an alpha of 0.05. Apart from that, the contrasting condition is that EA is needed to see the influence of ATGB with GPPI because the p-value of 0.001 is small compared with alpha 0.05, whose contribution is 0.161. This study has practical implications for managers. First, Generation Y should be educated to increase their awareness of using green products. Second, managers should increase the use of media to educate customers about the added value of green products to businesses, which will impact consumer purchase intentions, such as by saving energy and increasing the use of recycled materials. The government can increase public awareness of the negative impacts of environmental degradation, for example, pollution and the effects of greenhouse gases. Consumers will also have a high GPPI if they have a positive ATGB and know that a company's environmentally friendly brand attributes are high. This study has significantly improved our understanding of the literature on eco-friendly cars but has several limitations. First, the participants were young consumers (Generation Y). Future research should focus on all customers, including children, individuals with jobs, and stay-at-home moms. Second, this study did consider several other variables that might affect the inclination of consumers to buy green products. Thus, future research must propose further elements that support consumer intentions to GPPI, for example, incorporating moderating factors, such as age and gender, which can cite empirical findings that are vital for managerial decision-making and can help increase the acceptability of green products to raise awareness of environmental issues. The responses of individuals of various ages and genders to each GBP component may vary. Additionally, ATGB, knowledge of green brands, and intentions to GPPI are becoming importantfor young people. Third, this study was limited to car technology brands only. Thus, further studies should examine young consumers' perceptions of sustainability, such as consuming organic products and using eco-friendly services. There are also additional study methodologies, such as longitudinal, in which data may be gathered multiple times. Therefore, future research with a longitudinal design can be conducted.

AUTHOR CONTRIBUTIONS

A.S. Rama, the corresponding and first author, supervised in analyzing the data, interpreted the results, and prepared the manuscript. Y. Yasri, the second author, analyzed the data, interpreted the results, and prepared the manuscript. P. Susanto, the third author, analyzed the data, interpreted the results, and prepared the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest regarding the publication of this manuscript. Additionally, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
x	Multiplication sign
=	Equal sign
λ	Loading value
<	Small sign
( )	Brackets sign
β	Beta
P	Probability
ATGB	Attitude towards green brands
AVE	Average variance extracted
EA	Environmental awareness
et al.	et alia
Fig.	Figure
LCGC	Low-Cost Green Cars
GBP	Green brand positioning
GPPI	Green products purchase intention
GBK	Green brand knowledge
IDR	Indonesian rupiah
i.e.	Id est
SEM	Structural equation modeling
PLS	Partial least squares
H	Hyphotesis
H1	Hyphotesis 1
H2	Hyphotesis 2
H3	Hyphotesis 3
H4	Hyphotesis 4
H5	Hyphotesis 5
H6	Hyphotesis 6
H7	Hyphotesis 7
H8	Hyphotesis 8
H9	Hyphotesis 9
H10	Hyphotesis 10
HTMT	Heterotrait–monotrait
USD	United States Dollar
VIF	Variance inflation factor

REFERENCES

Abd'Razack, N.T.; Medayese, S.O.; Shaibu, S.I.; Adeleye, B.M., (2017). Habits and benefits of recycling solid waste among households in Kaduna, North West Nigeria. Sustai. Cities Soc., 28: 297-306 **(10 pages)**.

Aimon, H.; Kurniadi, A.P.; Amar, S., (2021). Analysis of fuel oil consumption, green economic growth and environmental degradation in 6 Asia Pacific countries. Int. J. Sustain. Dev. Plan., 16(5): 925-933 **(9 pages)**.

Aimon, H.; Kurniadi, A.P.; Amar, S., (2023). Scenario of reducing carbon emission through shifting consumption of non-renewable energy to renewable energy in asia pacific 2023-2030. IOP Conf. Ser. Earth Environ. Sci., 1151(1): 1-10 **(10 pages)**.

Almodarresi, A.S.M.; Tabataba'i-Nasab, S.M.; Bagheri, G.H.; Mohammadi, F., (2019). Does citizenship behavior have a role in changing attitude toward green products?. Int. J. Manag. Sci. Eng. Manage., 14(4): 284-292 **(9 pages)**.

Baiquni, A.M.; Ishak, A., (2019). The green purchase intention of Tupperware products: the role of green brand positioning. J. Siasat Bisnis. 23(1): 1-14 **(14 pages)**.

Braun, T.; Cottrell, R.; Dierkes, P., (2018). Fostering changes in attitude, knowledge and behavior: Demographic variation in environmental education effects. Environ. Educ. Res., 24(6): 899-920 **(22 pages)**.

Candrianto, C.; Aimon, H.; Sentosa, S.U., (2023). The role of knowledge, awareness and environmental attitudes in green product management. Glob. J. Environ. Sci. Manag., 9(1): 101-112 **(12 pages)**.

Cheah, I.; Phau, I., (2011). Attitudes towards environmentally friendly products: The influence of ecoliteracy, interpersonal influence and value orientation. Mark. Intell. Plan., 29(5): 452-472 **(21 pages)**.

Chen, M.F., (2009). Attitude toward organic foods among Taiwanese as related to health consciousness, environmental attitudes, and the mediating effects of a healthy lifestyle. Br. Food J., 111(2): 165-178 **(14 pages)**.

Chen, Y.S., (2010). The drivers of green brand equity: Green brand image, green satisfaction, and green trust. J. Bus. Ethics, 93(2): 307-319 **(13 pages)**.

Chen, Y.S.; Chang, C., (2012). Enhance green purchase intentions: The roles of green perceived value, green perceived risk, and green trust. Manag. Decis., 50(3): 502- 520 **(19 pages)**.

Cronin, J.J.; Smith, J.S.; Gleim, M.R.; Ramirez, E.; Martinez, J.D., (2011). Green marketing strategies: An examination of stakeholders and the opportunities they present. J. Acad. Mark. Sci., 39(1): 158-174 **(17 pages)**.

Dangelico, R.M.; Vocalelli, D., (2017). Green marketing: An analysis of definitions, strategy steps, and tools through a systematic review of the literature. J. Clean. Prod., 165: 1263-1279 **(17 pages)**.

Darmawan, D.P.; Arisena, G.M.K.; Djelantik, A.A.A.W.S.; Krisnandika, A.A.K.; Dewi, N.L.M.I.M.; Korri, N.T.L.; Sukendar, N.M.C., (2023). Farmers' motivation and obstacles in the smallest available agricultural region. Global J. Environ. Sci. Manage., 9(4): 967-982 **(16 pages).**

Hair Jr, J.F.; Hult, G.T.M.; Ringle, C.M.; Sarstedt, M.; Danks, N.P.; Ray, S., (2021). Partial least squares structural equation modeling (PLS-SEM) using R: A workbook. pp. 197. Springer Nature.

Hartmann, P.; Ibanez, V.A.; Sainz, J.F., (2005). Green branding effects on attitude: functional versus emotional positioning strategies. Mark. Intell. Plan., 23(1): 9-29 **(21 pages)**.

Himawan E., (2019).Pengaruh green brand positioning, green brand attitude, green brand knowledge] terhadap green purchaseintention. JMBK, 3(2): 110-115 **(6 pages)**.

Huang, Y.C.; Yang, M.; Wang, Y.C., (2014). Effects of green brand on green purchase intention. Mark. Intell. Plan., 32(3): 250-268 **(19 pages)**.

Kang, S.; Hur, W.M., (2012). Investigating the antecedents of green brand equity: A sustainable development perspective. Corp. Soc. Respons. Environ., 19(5): 306-316 **(11 pages)**.

Kautish, P.; Paul, J.; Sharma, R., (2019). The moderating influence of environmental consciousness and recycling intentions on green purchase behavior. J. Clean. Prod., 228: 1425-1436 **(12 pages)**.

Kim, J.H.; Lee, B.W.; Schroeder, F.C.; Jander, G., (2008). Identification of indole glucosinolate breakdown products with antifeedant effects on Myzus persicae (green peach aphid). Plant. J., 54(6): 1015-1026 **(12 pages)**.

Kolbadinezhad, R.; Mahdiraji, E.A., (2021) Evaluation and Selection of Construction Industry Contractors as an Optimal Model from the Perspective of Health, Safety and Environment. Eurasian J. Sci. Tech., 1(3): 131-141 **(11 pages).**

Komaladewi, R.; Indika, D., (2017). A review of consumer purchase decision on low cost green car in West Java, Indonesia. Rev. Integr. Bus. Econ. Res., 6(2): 172-184 **(13 pages)**.

Kurniadi, A.P.; Aimon, H.; Amar, S., (2022). Analysis of green economic growth, biofuel oil consumption, fuel oil consumption and carbon emission in Asia Pacific. Int. J. Sustain. Dev. Plan., 17(7): 2247-2254 **(8 pages)**.

Kurniadi, A.P.; Aimon, H.; Amar, S., (2021). Determinants of biofuels production and consumption, green economic growth and environmental degradation in 6 Asia Pacific Countries: a simultaneous panel model approach. Int. J. Energy Econ. Policy, 11(5): 460-471 **(12 pages)**.

Law, M.M.S.; Hills, P.; Hau, B.C.H., (2017). Engaging employees in sustainable development–a case study of environmental education and awareness training in Hong Kong. Bus. Strategy Environ., 26(1): 84-97 **(14 paages)**.

Leaniz, M.G.P.; Herrero, Á.; Gómez, L.R., (2018). Customer responses to environmentally certified hotels: The moderating effect of environmental consciousness on the formation of behavioral intentions. J. Sustain. Tour., 26(7): 1160-1177 **(18 pages)**.

Lee, K., (2008). Opportunities for green marketing: young consumers. Mark. Intell. Plan., 26(6): 573-586. **(14 pages)**.

Lin, Y.C.; Chang, C.A., (2012). Double standard: The role of environmental consciousness in green product usage. J. Mark., 76(5): 125-134 **(10 pages)**.

Lin, J.; Lobo, A.; Leckie, C., (2017). Green brand benefits and their influence on brand loyalty. Mark. Intell. Plan., 35(3): 425-440 **(16 pages)**.

Mehraj, D.; Qureshi, I.H., (2022). Does green brand positioning translate into green purchase intention?: A mediation–moderation model. Bus. Strategy Environ., 31(7): 3166-3181 **(16 pages)**.

Mostafa, M.M., (2007). Gender differences in Egyptian consumers' green purchase behaviour: The effects of environmental knowledge, concern and attitude. Int. J. Consum. Stud., 31(3): 220-229 **(10 pages)**.

Naalchi, K.A., (2020). Green purchase intention: A conceptual model of factors influencing green purchase of Iranian consumers. J. Islam. Mark., 11(6): 1389-1403 **(15 pages)**.

Paul, J.; Modi, A.; Patel, J., (2016). Predicting green product consumption using theory of planned behavior and reasoned action. J. Retail. Consum. Serv., 29: 123-134 **(12 pages)**.

Rex, E.; Baumann, H., (2007). Beyond ecolabels: What green marketing can learn from conventional marketing. J. Clean. Prod., 15(6): 567-576 **(10 pages)**.

Rios, M.F.J.; Martinez, L.T.; Moreno, F.F.; Soriano, C.P., (2006). Improving attitudes toward brands with environmental associations: an experimental approach. Consum Mark., 23(1): 26-33 **(8 pages)**.

Samimi, M.; Moghadam, H., (2024). Modified evacuated tube collector basin solar still for optimal desalination of reverse osmosis concentrate. Energy, 289: 129983 **(8 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Sana, S.S., (2020). Price competition between green and non green products under corporate social responsible firm. J. Retail. Consum. Serv., 55(102118): 1-17 **(17 pages)**.

Shaykh-Baygloo, R., (2021). Foreign tourists' experience: The tri-partite relationships among sense of place toward destination city, tourism attractions and tourists' overall satisfaction-Evidence from Shiraz, Iran. J. Dest. Mark. Manage., 19: 1-16 **(16 pages)**.

Situmorang, T.P.; Indriani, F.; Simatupang, R.A.; Soesanto, H., (2021). Brand positioning and repurchase intention: The effect of attitude toward green brand. J. Asian Fin. Econ. Bus., 8(4): 491-499 **(9 pages)**.

Siyal, S.; Ahmed, M.J.; Ahmad, R.; Khan, B.S.; Xin, C., (2021). Factors influencing green purchase intention: Moderating role of green brand knowledge. Int. J. Environ. Res. Public Health, 18(20): 1-22 **(22 pages)**.

Smith, S.; Paladino, A., (2010). Eating clean and green? Investigating consumer motivations towards the purchase of organic food. Australas. Mark. J., 18(2): 93-104 **(12 pages)**.

Sreen, N.; Purbey, S.; Sadarangani, P., (2018). Impact of culture, behavior and gender on green purchase intention. J. Retail. Consum. Serv., 41: 177-189 **(13 pages)**.

Suki, M.N., (2016). Green product purchase intention: impact of green brands, attitude, and knowledge. Br. Food J ., 118(12): 2893-2910 **(8 pages)**.

Tian, Z.; Sun, X.; Wang, J.; Su, W.; Li, G., (2022). Factors affecting green purchase intention: A perspective of ethical decision making. Int. J. Environ. Res. Public Health. 19(18): 1-16 **(16 pages)**.

Villagra, N.; Monfort, A.; Herrera, S.J., (2021). The mediating role of brand trust in the relationship between brand personality and brand loyalty. J. Consum. Behav., 20(5): 1153-1163 **(11 pages)**.

Wang, Y.M.; Zaman, H.M.F.; Alvi, A.K., (2022). Linkage of green brand positioning and green customer value with green purchase intention: The mediating and moderating role of attitude toward green brand and green trust. Sage Open. 12(2): 21582440221102441.

White, K.; Habib, R.; Hardisty, D.J., (2019). How to SHIFT consumer behaviors to be more sustainable: A literature review and guiding framework. J. Mark., 83(3): 22-49 **(28 pages)**.

Woo, E.; Kim, Y.G., (2019). Consumer attitudes and buying behavior for green food products: From the aspect of green perceived value (GPV). Br. Food. J., 121(2): 320-332 **(13 pages)**.

Yasir, D.H.; Ali, N.A., (2021) Effect of Adding Different Levels of Lemon Grass Leaves Cymbopogon Citratus to the Diet and Its Extract in Drinking Water on Productive Performance of Broiler Chickens (Ross 308). Eurasian J. Sci. Tech., 2021, 1(1):1-10 **(10 pages).**

Zameer, H.; Yasmeen, H., (2022). Green innovation and environmental awareness driven green purchase intentions. Mark. Intell. Plan., 40(5): 624-638 **(15 pages)**.

Zavali, M.; Theodoropoulou, H., (2018). Investigating determinants of green consumption: evidence from Greece. Soc. Responsible J., 14(4): 719-736 **(18 pages)**.

Zhou, Z.; Zheng, F.; Lin, J.; Zhou, N., (2021). The interplay among green brand knowledge, expected eudaimonic well-being and environmental consciousness on green brand purchase intention. Corp. Soc. Respons. Environ Manage., 28(2): 630-639 **(10 pages)**.

Zhuang, W.; Luo, X.; Riaz, M.U., (2021). On the factors influencing green purchase intention: A meta-analysis approach. Front. Psychol., 12(644020): 1-15 **(15 pages)**.

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ORIGINAL RESEARCH PAPER

A suitability modeling based on geographic information system for potential micro hydropower dam site

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ABSTRACT

BACKGROUND AND OBJECTIVES: Micro-hydropower plants are significant contributors of electricity and clean source of renewable energy. A nationwide or large watershed inventory of potential micro hydropower dam sites is lacking, hindering micro-hydropower development. Traditional ground survey approaches for locating micro-hydropower dam sites are expensive, time-consuming, laborious, and vulnerable to inconsistency. Geographic information system frameworks are commonly used, and they provide significant value to hydropower evaluation. A suitability approach for dam site identification is important in supporting the optimization of hydropower utilization in the context of watershed management and in eliminating the inconsistency of conventional approaches. The objective of this study was to identify potential sites for micro-hydropower dams on the basis of various parameters by using a suitability modeling approach based on geographic information system.

METHODS: The Saddang Watershed was chosen as the study area, it is located in the South Sulawesi and West Sulawesi Provinces of Indonesia, and it is an example of a large watershed. The analytical hierarchy process was used for criterion weighting and to create a dam suitability index map based on the following criteria: geomorphometry, geology, rainfall, soil texture, and land use land cover. The developed dam suitability index map was validated by comparing it with existing dams by using the receiver operating characteristic curve. The identification of potential micro-hydropower dam sites involved overlay and query methods. It considers dam suitability index, proximity from road and settlement, existence of conservation forest, and the potential hydraulic head.

FINDINGS: The dam suitability index map with five suitability classes was obtained, with the high and very high suitability indexes extending to 8.7 percent of the study area. These classes were typified by high drainage density, topographic wetness index, stream power index, low vegetation cover, moderate slope, situated on second or higher stream orders, normal temporal distribution of rainfall, and sandy clay loam soil texture with igneous and sedimentary complex rocks. The developed suitability model was sufficiently effective in determining dam suitability index, as indicated by a value greater than 0.9 of the area under the curve. A total of 635 potential dam locations were identified with high and very high suitability indexes, located on first or second stream orders, within a 4,000 m radius of roads and settlements, outside conservation forest areas, and with a potential hydraulic head greater than 20 meter.

CONCLUSION: Integrating a dam suitability index map and restriction factors into a geographic information system framework, enabled a robust analysis for identifying potential sites of micro-hydropower dams. The proposed approach is expected to contribute to the advancement of renewable energy initiatives and water resource management within large watersheds. It is also expected to serve as a valuable resource for policymakers involved in the implementation of micro-hydropower projects and watershed management to support the achievement of renewable energy development targets.

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INTRODUCTION

Electricity consumption and availability serve as indicators of the socio-economic development of a particular region. Electricity is also recognized as a catalyst for enhancing various forms of production and as a lever for economic development (Lee and Chang, 2018). Approximately 80 percent (%) of energy consumption is derived from fossil fuels, highlighting society's heavy reliance on non-renewable energy sources (Samimi and Moghadam, 2024). Such dependency has also contributed to the issue of climate change (Harjanne and Korhonen, 2019; Frimawaty *et al.,* 2023). Exploring renewable energy sources is imperative due to possible consequences for developing and developed nations (Hammid *et al.,* 2018). The adoption of renewable sources is also a critical strategy for mitigating environmental effects from carbon dioxide (CO_2) emissions within the energy sector (Olabi and Abdelkareem, 2022). Among renewable energy sources, micro-hydropower plant (MHP) is a prominent contributor to electricity generation (García *et al.,* 2021) and it represents a cleaner energy source (Bayazıt *et al.,* 2017). MHP exhibits the advantage of supporting electricity supplies to remote areas, and thus, it improves energy quality and socio-economic development (Pottmaier *et al.,* 2013). Hydropower also constitutes a substantial portion of global renewable energy development, contributing 71% of the total supply and approximately 16.4% of the world's electricity (Moran *et al.,* 2018). MHP development remains challenging, particularly in regions with rich water resources, such as Asia, and Latin America. One of the primary impediments to MHP development is the absence of the latest national/regional data and information on potential dam sites for MHP initiatives (Odiji *et al.,* 2021). Traditional ground survey methods for identifying potential MHP dam sites are cost-prohibitive, time-intensive, and labor-demanding, necessitating focused investigations in areas that are likely to yield suitable sites. Determining potential locations for MHP dams at the regional scale still uses a data aggregation approach with varying accuracy and is vulnerable to inconsistencies (Ali *et al.*, 2023), resulting in differences and inconsistencies between data and collection methods (Korkovelos *et al.*, 2018). Improving the quality and consistency of dam location identification for MHP is a prerequisite for supporting planning before the structural development. Geographic information systems (GIS) have emerged as effective tools for spatial data analysis, including the exploration of potential dam sites for MHP projects. GIS-based approaches for hydropower assessment offer several advantages, such as enhancing efficiency and accuracy in the context of data integration, visualization and analysis, and addressing the issues of complex analysis, considerable time consumption, risk assessment, adaptability, and iteration (Zewdie and Tesfa, 2023). GIS approaches have also gained prominence in spatial modeling by conveying valuable and significant information, including the incorporation of remote sensing (RS) and GIS methods for hydropower assessment. The utilization of GIS-based modeling assists in evaluating potential MHP dam sites by considering various parameters that influence site selection (Avtar *et al.,* 2019). Numerous studies have emphasized the utility of RS and GIS techniques in hydropower development. For example, Othman *et al.* (2020) utilized GIS-RS in the selection of appropriate hydropower dam sites in the Kurdistan Region of Iraq by using the Weighted Sum Method (WSM) and Analytical Hierarchy Process (AHP) approaches and by integrating multiple data layers. A study in Thailand incorporated GIS and AHP to assess potential small hydropower sites on the basis of morphometric, climate, lithology, soil type, slope, and land use land cover (LULC) (Ali *et al.,* 2023). Although some studies have explored dam site suitability, limited attention has been given to the explicit elucidation of the spatial identification of potential dam sites with the incorporation of socio-economic factors, conservation forest existence, and technical aspects (potential hydraulic head). Indonesia, the country under consideration, exhibits a remarkable hydrological configuration distinguished by numerous precipitations and a sophisticated river network. The presence of 23.3 million hectares (ha) of state-owned forests (Ministry of Environment and Forestry, 2020) assumes a pivotal role in hydrological regulation, facilitating the provision of the water resources which is integral to advancing MHP initiatives. The country has a hydropower potential of up to 75 Giga Watt (GW), including rivers that drain water from forest ecosystems (Rahayu and Windarta, 2022). MHP development in Indonesia is supported by the National Electricity Company, which aims to develop 0.3 GW MHP in 2016-2025. In accordance with the document of the National Energy General Plan, to achieve a minimum of 23% new renewable energy by 2025, hydropower plants with a total capacity of at least 18 GW and MHPs of 3 GW, representing 46.4% of the total new renewable energy target, will be built. It shows that both currently and in the future, data and information on potential MHP dam sites in the region/provinces/large watersheds are needed to support the sustainability of national electricity through MHP development. This study addresses the limitations presented in previous research by introducing an approach that identifies stream channel segments with the intersection of the Dam Suitability Index (DSI), proximity from roads and settlements, conservation area boundaries, stream order, and potential hydraulic head. The objective is to enhance the spatial identification of dam sites for MHP development, particularly within large watersheds. This study performed the following procedures to achieve its objective: 1) evaluating and mapping geomorphometry, climate, geology, soil texture, and LULC factors; 2) applying AHP to generate a DSI map; and 3) identifying potential sites for MHP dam. The study findings will provide resource managers and energy planners, who are constrained by data limitations, with valuable insights for identifying promising locations for MHP dams, mitigating expenditures of time and resources in subsequent field investigations. Suitability modeling is also important for supporting watershed management in terms of micro-hydropower optimization and reducing inconsistency in both data, method, and results. This study was conducted in the Saddang Watershed, South Sulawesi and West Sulawesi Provinces, Indonesia, in 2023.

MATERIALS AND METHODS

The methodological flow chart of this study is presented in Fig. 1. This section elucidates the study area description, the diverse types of utilized data,

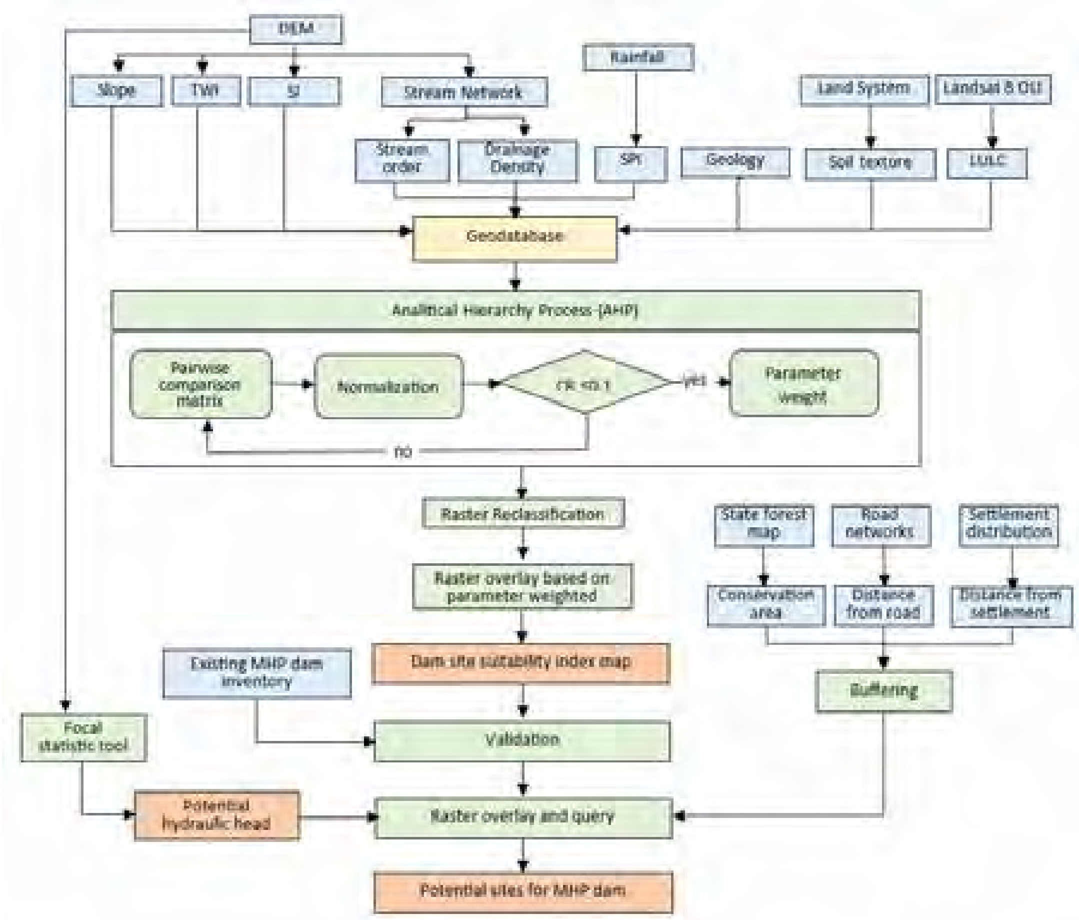

Fig. 1: The methodological flow chart of this study

Fig. 2: Geographic location of the study area in Saddang Watershed in west and south Sulawesi Provinces of Indonesia

and the data processing and analysis techniques employed to identify potential sites for MHP dam development. The Digital Elevation Model (DEM) data used in this study were obtained from the Geospatial Information Agency of Indonesia. The spatial resolution of the DEM data is 8.3 meters (m) (Sihombing *et al.*, 2021). The geological characteristics of the study area were extracted from the Geology map of Indonesia, particularly the Sulawesi sheet, with a scale of 1: 250,000 (Villeneuve *et al.*, 2002). The soil texture of the study area was derived from the land system map released by the Geospatial Information Agency. The Landsat Operational Land Imager (OLI) 8, with a spatial resolution of 30 m (Roy *et al.*, 2014) and acquisition year 2022, was downloaded from the United States Geological Survey website and used to obtain the LULC of the study area. This study utilized rainfall data from the Climate Hazards Group Infra-Red Precipitation with Station (CHIRPS) (Funk *et al.*, 2015). The spatial distributions of road networks and settlements were isolated from Indonesia's Topographic Map with a scale of 1:50,000 produced by the Geospatial Information Agency of Indonesia. The conservation forest situated in the study area was clipped from the State Forest of Indonesia map released by the Ministry of Environment and Forestry of Indonesia (Ministry of Forestry, 2014). The distribution of existing dam sites of MHP in the study area was obtained from Remap Indonesia (Wahyuono and Julian, 2018) for validation purposes.

Study area

This study selected the Saddang Watershed as the object. It is predominantly located in South Sulawesi Province, and a small portion also extends into the West Sulawesi Province, Indonesia (Fig. 2). The watershed covers an area of about 6,630 square kilometers (km^2). The Saddang Watershed is situated between 119°15'20" and 120°03'52" east (E) and between 2°44'20" and 3°46'20" south (S). It constitutes a hydrological basin with a considerable expanse, encompassing Mamuju, Mamasa, and Polewali Mandar Districts in West Sulawesi, and Tanah Toraja, Enrekang, and Pinrang Districts in South Sulawesi. The watershed plays a significant role in shaping the hydrological cycle, ensuring the accessibility and availability of water resources in the context of land governance. Its pivotal role extends to providing essential irrigation for agricultural activities, with effluents discharging at the Bendeng Reservoir, located within the jurisdictions of Pinrang and Sidrap Districts (Irmayani *et al.,* 2018). The climate type of the Saddang Watershed is type C according to the Schmidt-Ferguson classification, corresponding to a slightly wet region. The annual rainfall in the area is 2,155 millimeters (mm), with April experiencing the highest monthly average rainfall and August the lowest. Forest coverage (75%) dominates the LULC of the Saddang Watershed, distributed mainly in the upstream areas (Irmayani *et al.,* 2018). The dominant rock formation is the Talaya Volcano Rock, encompassing 25% of the total area. Mountains/hills landforms dominate the geomorphology of the Saddang Watershed. Most of the watershed areas have slopes between 25% and 45% (Lamada *et al.,* 2022).

Criteria determination for MHP dam site identification

Site selection that is most conducive to establishing MHP structures took into consideration various criteria, including geomorphometry, topography (Ajibade *et al.,* 2020), geology, and climate (Othman *et al.,* 2020). Nine criteria were considered in the DSI mapping within the study area: flow continuity (stream order), geology, slope, soil texture, Drainage density (Dd), Topographic Wetness Index (TWI), Stream power Index (SI), Standardized Precipitation Index (SPI), and LULC. The criteria were adopted on the basis of a comprehensive literature review of previous studies related to hydropower evaluation and data availability consideration.

Flow continuity (stream order)

A crucial criterion for locating an MHP dam is the amount of water flow that is reliably accessible all year round. An adequate water discharge must be available to operate MHP effectively. Flow potential in this study was represented by the stream order criterion in which higher order specifies flow accumulation. A high flow accumulation value of a particular region is expected to represent water bodies more precisely, such as rivers, ponds, and lakes (Korkovelos *et al.,* 2018). Stream order criterion aids in identifying streams where water flow is likely to exceed a certain minimum threshold throughout the year. The stream network was generated from DEM by using a threshold accumulation value of 1,000 in the GIS environment and the Strahler stream order method. Fig. 3a depicts the stream order in the watershed being studied, and it ranges from first to eighth order. The length of the first order stream reaches 51% of overall stream length in the watershed.

Rainfall

Rainfall intensity exerts a significant influence on peak discharge. An increase in the amount of rainfall directly effects increased river discharge, including peak discharge. The potential for electricity generation in an area depends on rainfall volume, intensity, and spatial distribution (Zhao *et al.,* 2019). In this study, the rainfall criteria were represented by SPI. SPI assesses the deviation of precipitation data from its long-term average, thereby providing insights into the variability and intensity of precipitation events. It also considers the temporal distribution of precipitation and is applicable over various timescales (Gidey *et al.,* 2018). SPI was calculated for periods of the dataset using Eq. 1 (Livada and Assimakopoulos, 2007).

$$SPI = \frac{x_i - \bar{x}}{\sigma} \quad (1)$$

Where; x_i represents monthly rainfall, $\bar{x}$ represents mean monthly rainfall, and σ denotes the standard deviation of rainfall. The resulting SPI calculation for the entire study area is presented in

Fig. 3b. The temporal distribution of rainfall in the study watershed shown by SPI ranged from 0.49 to 0.97. This result indicated that rainfall distribution is normal (SPI = -0.99 to 0.99) and spread throughout the year (Anshuka *et al.,* 2019).

Geology

The geological substrate that underlies a dam structure represents a critical determinant that is integral to a dam's foundation. Geologically strong materials, (e.g. hard rock formations), are highly

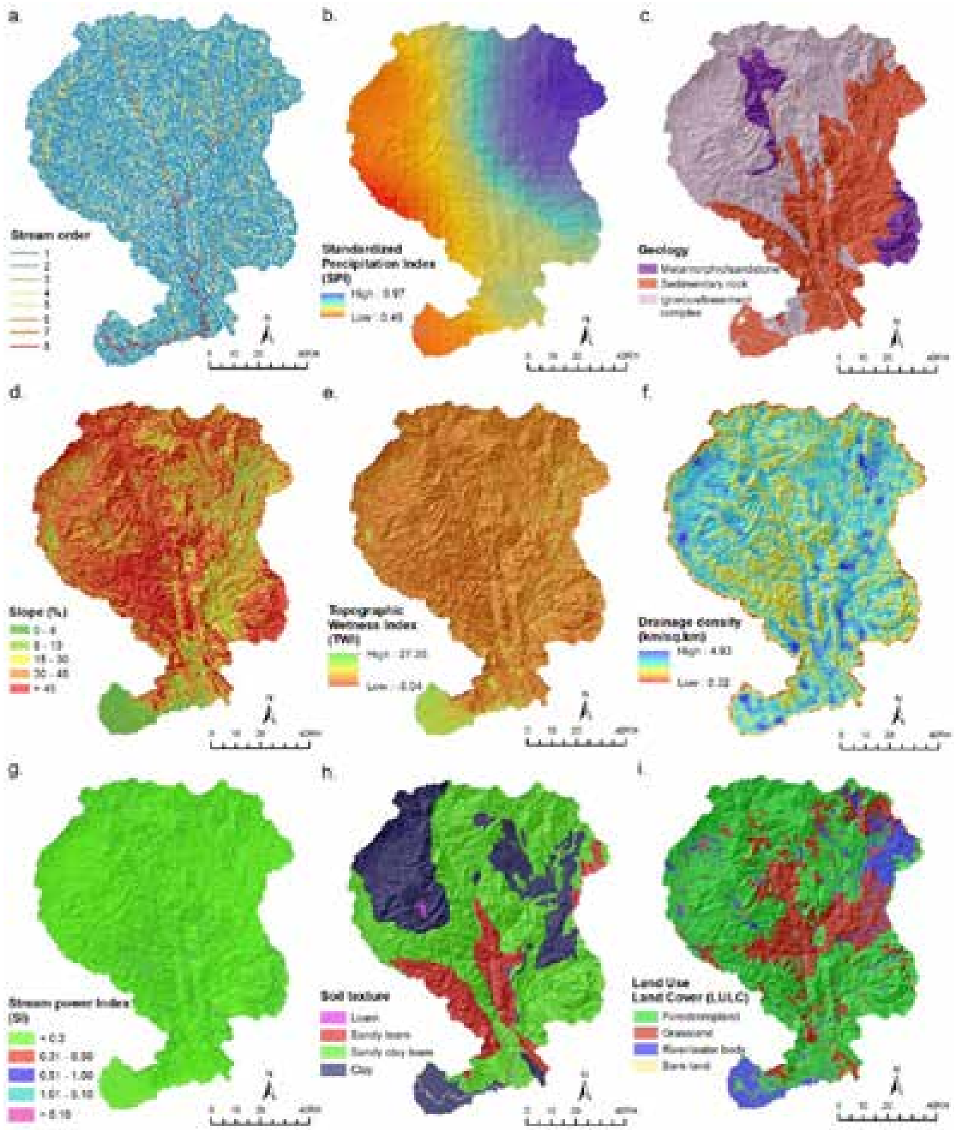

Fig. 3: Maps of criteria used in the analysis: stream order (a), SPI (b), geology (c), slope (d), TWI (e), Drainage density (f), SI (h), soil texture (h), and LULC (i).

suitable materials for dam construction (Sissakian *et al.,* 2020). The geological feature under MHP dam must possess the requisite strength to support the weight of the dam structure and water reservoir. The geological landscape of the study area can be generally categorized into three distinct formations: igneous/basement complex, sedimentary rock complex, and metamorphic/sandstone formation. The spatial distribution of geology in the study area is presented in Fig. 3c.

Slope

Slope exerts a profound influence on the pattern and magnitude of surface runoff. An escalation in slope steepness corresponds directly to an augmentation of river flow velocity (Yu *et al.,* 2022). Slope is also an elemental determinant of hydropower initiation, where a greater slope gradient creates a heightened power yield, and conversely, a reduced gradient diminishes power output. The slope layer in this study was generated from the DEM dataset. Fig. 3d provides a graphical depiction of slope characteristics, revealing predominant steepness in the northern part with gradual inclinations discernible in the central and southern regions of the study watershed.

Topographic wetness index

TWI functions as a representation metric for identifying regions that accumulate runoff potential. It is employed in elucidating the dynamics of water flow and accumulation (Meles *et al.,* 2020). TWI values were extracted from the DEM using Eq. 2 (Hojati and Mokarram, 2016).

$$TWI=\ln\left[\frac{A}{\tan(\beta)}\right] \quad (2)$$

Where; A is the catchment area, and β is the slope gradient in degrees. Fig. 3e shows the TWI distribution in the study area. The TWI values in the study watershed were between -5.04 and 27.3 5. The higher values predominantly correspond to the central watershed, especially along the primary river network and in the southern part of the study watershed.

Drainage density (Dd)

Drainage density denotes the total stream lengths per watershed area. It serves as an indicator of the tendency for surface runoff and groundwater presence within a specified area. Regions marked by elevated drainage density are characterized by a heightened susceptibility to surface runoff and groundwater occurrence, making them amenable to hydropower generation applications (Allafta *et al.,* 2021). Stream network data were used to generate drainage density through the spatial analysis method, specifically the line density tool. The drainage density in the study area was between 0.32 km/km^2 and 4.93 km/km^2 (Fig. 3f).

Stream power index (SI)

SI is a valuable tool for quantifying the potential for flow erosion at a specific location on a topographic surface. The corresponding rise in the volume of water contributed by the upslope catchment area and the velocity of water flow are followed by an increase in the upslope catchment area and slope gradient (Andualem *et al.,* 2020), resulting in an increase in the SI values and the potential erosion effects. Eq. 3 was utilized to calculate the SI value based on the DEM dataset (Papangelakis *et al*., 2022).

$$SI=\ln[A \, . \, \tan(\beta)] \quad (3)$$

Where; A is catchment area, and β is the slope gradient in degrees. Fig. 3g presents the SI map of the study area. SPI values varied between -6.07 and 15.65 within the study area.

Soil texture

Soil texture correlates closely to the infiltration process and runoff generation. The textural composition of the soil is a pivotal factor in identifying an appropriate site for MHP dam construction, particularly in the context of dam foundation (Al-Ruzouq *et al.,* 2019). The soil texture map of the study watershed was extracted from the Land System map. Fig. 3h illustrates an overview of the soil texture distribution in the Saddang Watershed, divided into four classes: loam, sandy loam, sandy clay loam, and clay.

Land use land cover (LULC)

LULC can be defined as the allocation and deployment of land for distinct purposes. It effects surface roughness, soil infiltration capacity, runoff generation, and the patterns of peak discharge within a watershed, providing essential consideration in MHP dam site selection (Abdulkareem *et al.,* 2019). LULC data were obtained by interpreting Landsat 8 OLI by using a supervised classification approach, i.e., the maximum likelihood method. Fig. 3i presents LULC distribution in the study area, indicating that forest and cropland encompass 66% of the study area. Bare land accounts only for 0.2%, while the combination of grassland and water bodies occupy 33.8% of the study area.

Analytical hierarchy process (AHP)

AHP is a widely adopted approach for Multi-Criteria Decision-Making (MCDM). The method is widely used in evaluating the suitability of sites for various purposes. This study created a 9x9 pairwise comparison matrix (Table 1), in which every criterion was subjected to ranking vis-à-vis the others, on the basis of Saaty's scale of 1-9 (Saaty, 2008) which was derived from the collective insights of an extensive review of relevant literature. A normalized matrix was then constructed through column-wise division

Table 1: Pairwise comparison matrix of AHP for MHP dam site suitability index mapping

Criteria	Stream order	SPI	Geology	Dd	Slope	TWI	SI	Soil texture	LULC	Normalized weight
Stream order	1.00	4.00	5.00	5.00	5.00	4.00	3.00	3.00	4.00	0.30
SPI	0.25	1.00	3.00	4.00	2.00	4.00	3.00	3.00	3.00	0.17
Geology	0.25	0.33	1.00	2.00	2.00	2.00	3.00	2.00	2.00	0.10
Dd	0.25	1.00	1.00	1.00	2.00	3.00	2.00	4.00	2.00	0.12
Slope	0.25	0.33	1.00	0.50	1.00	3.00	2.00	3.00	2.00	0.09
TWI	0.25	0.33	0.50	0.50	0.50	1.00	2.00	2.00	2.00	0.07
SI	0.25	0.25	0.50	0.33	0.50	0.50	1.00	2.00	2.00	0.06
Soil texture	0.25	0.25	0.50	0.50	0.33	0.50	0.50	1.00	1.00	0.04
LULC	0.25	0.25	0.50	0.50	0.50	0.50	0.50	1.00	1.00	0.05
Total	3.02	7.33	11.83	14.08	13.67	18.50	17.00	21.00	19.00	1.00
Consistency index										0.06
Random index										1.45
Consistency ratio										0.04

by the sum of the respective columns. The total scores of each criterion in the pairwise comparison were computed. Subsequently, the average of each row in the normalized matrix was calculated to obtain the criterion weight. An assessment was conducted to determine the consistency of criteria ratings throughout the paired comparison criteria and the obtained criterion weight. Such evaluation is essential for optimizing the priority scale and reducing subjectivity among the criteria used. Consistency Ratio (CR) was used in the evaluation by using Eqs. 4 and 5 (Saaty, 2008).

$$CI= \frac{\lambda_{max}-n}{n-1} \quad (4)$$

$$CR= \frac{CI}{RCI} \quad (5)$$

Where; CI is the consistency index, λ_{max} is the maximum eigenvalue, n is the number of criteria, CR is the consistency ratio, and RCI is the random consistency index (1.45 for nine criteria). On the basis of the evaluation, the obtained CR was 0.04 (<0.10), indicating that the weight of the criteria was within the rational degree of consistency (Saaty, 2008). Sub-criteria were subjected to rankings (0 to 9) aligned with various previous studies and professional judgment, as detailed in Table 2. High scores were assigned to sub-criteria with substantive influence, while sub-criteria exerting a minor influence obtained comparatively lower scores.

Overlay analysis for DSI map generation

DSI mapping used the overlay method in the GIS environment by combining the influences of criteria on the basis of criterion weight. All the criterion layers were transformed into a unified raster format, with their values being classified accordingly. The suitability index map was determined using Eq. 6 (Owolabi *et al.*, 2020).

$$DSI= \sum_{i=1}^{9} W_i (R_i) \quad (6)$$

Where; DSI is the Dam Suitability Index representing the assessment of the potential for dam suitability, W_i is criterion weight for i criteria determining the importance of each criterion in the evaluation, R_i is the sub- criterion score indicating the relative significance of each sub-criterion, and i...9 represents the nine criteria used.

Validation of the DSI map

Validation was conducted by comparing the predicted dam suitability map against the existing MHP dam in the study area. The area under the curve (AUC) of the Receiver Operating Characteristic (ROC) was utilized as the metric to validate predictive performance (Rahmati *et al.*, 2019). The ROC curve is a widely used technique for evaluating the accuracy of models in predicting spatial phenomena. The construction involves utilizing pairs of two numbers, namely the genuine positive rate and the false negative rate (Mohammady *et al.*, 2019). AUC

Table 2: Classification of criteria for weighted overlay analysis

Criteria	Weight	Sub-criteria	Score
Stream order	0.30	First order	2
		Second order	4
		Third order	6
		Fourth order	7
		Fifth or more order	9
Standardized precipitation index (SPI)	0.17	<2.00	3
		-1.5 - -11.99	4
		-1.00 - -1.49	5
		-0.99 - 0.99	6
		1.00 - 1.49	7
		1.50 - 1.99	8
		>2.00	9
Geology	0.10	Igneous/basement complex	9
		Sedimentary rock	6
		Metamorphic/sandstones	4
Drainage density (Dd) (km/km^{-2})	0.12	<0.49	2
		0.49 - 2.67	5
		2.68 - 3.44	7
		3.45 - 4.75	8
		>475	9
Slope (%)	0.09	0-8	9
		8-15	7
		15-25	5
		25-40	3
		>40	2
Topographic wetness index (TWI)	0.07	<4.0	3
		4.01 - 8.0	5
		8.01-13.0	7
		13.01 - 17.0	8
		>17.01	9
Stream power index (SI)	0.06	<0.30	2
		0.301-0.50	4
		0.501-1.01	5
		1.01-5.1	7
		>5.1	9
Soil texture	0.04	Loam	1
		Sandy loam	4
		Sandy clay loam	6
		Clay	7
		Silt	9
Land use land cover (LULC)	0.05	Forest	1
		Cropland	1
		Grassland	2
		Waterbody/river	7
		Bare land	9

values range from 0 to 1, with superior predictive performance indicated by values close to 1, whereas those around 0.5 suggest predictions approaching randomness (Pham and Prakash, 2018).

Restriction for dam site selection

Identifying potential dam sites in the study area was contingent upon the incorporation of factors, including the suitability index and limitation condition related to socio-economic considerations, such as proximity from road, settlement, and forest conservation area (Ali *et al.,* 2023). MHP dams situated farther away from roads are subject to more significant infrastructure expenses and encounter increased energy loss (Stepanov *et al.,* 2016). Proximity to settlement results in substantial cost reductions in the primary cable network infrastructure. The closeness of an MHP site to settlements can also have an effect on community engagement, land use conflicts, and environmental impacts, particularly for community-based MHP development. The existence of conservation forests also influences MHP dam selection because these areas are safeguarded by legislation. All potential dam locations in this study were considered to be outside conservation forest areas. These constraints were used to generate an unsuitable map for the MHP dam site. The Boolean technique was employed in this study (Table 3), in which 0 indicates unsuitable and 1 indicates permitted for MHP dam sites.

The Euclidean distance method was used to define proximity from road and settlement. The obtained proximity map was reclassified on the basis of restricted proximity and assigned the appropriate value. All restricted layers (Fig. 4) were subsequently incorporated and superimposed into the GIS environment, yielding binary values of 0 to denote unsuitable and 1 for suitable location of the MHP dam sites.

Identification of potential site for MHP dam

The potential site for MHP dam map was generated by combining the validated DSI, proximity to road and settlement, existence of conservation forest, and potential hydraulic head using overlay and query analysis within the GIS environment. The potential hydraulic head is the height differences between the dam and the powerhouse within a certain radius. In this study, the potential hydraulic head was calculated using a focal statistic tool in the GIS environment.

RESULTS AND DISCUSSION

This section is divided into several topics: DSI map for MHP, Validation of DSI map, Potential site for MHP dam, and Implication of the study result.

DSI map for MHP

A composite DSI layer was generated by incorporating all criteria and then categorising them into five distinct classes by utilizing the natural break method. Fig. 5 presents the spatial distribution of the suitability index for MHP dam sites. Various parts of

Table 3: Restriction factor for MHP dam site identification

Parameter	Condition	Assigned value
Forest states	Conservation forest	0
Distance from settlement	≤ 4000	1
	> 4000	0
Distance from road	≤ 4000	1
	> 4000	0

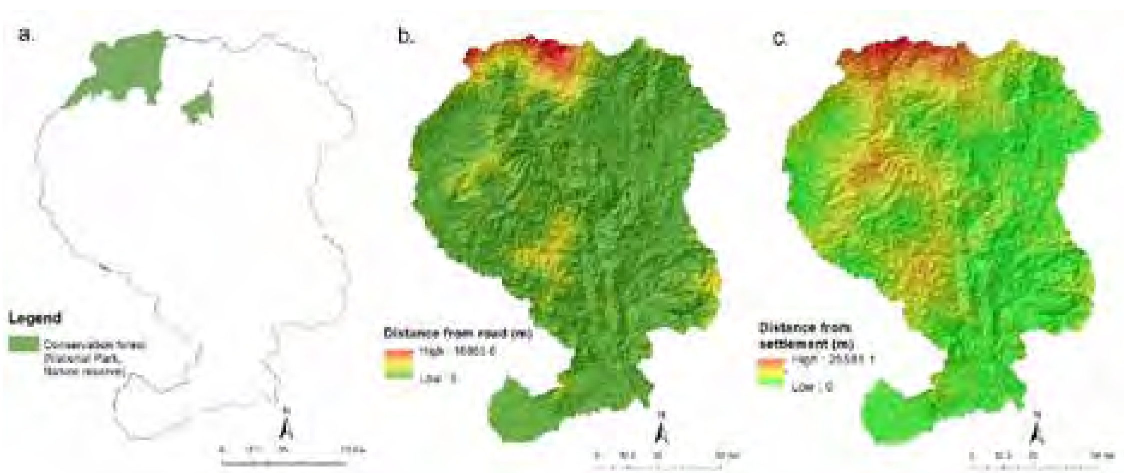

Fig. 4: Restricted map for MHP dam site selection: conservation forest (a), distance from road (b), and distance from settlement (c)

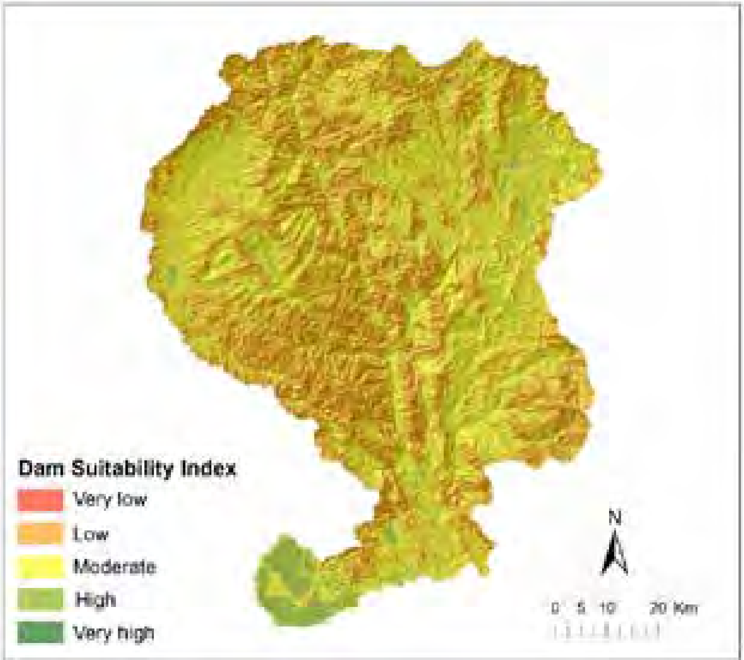

Fig. 5: Suitability index map for MHP dam site

a river may vary in their suitability for constructing MHP dams due to the diverse manifestations of the influencing elements being studied. The area classified with very high suitability is 41.4 km^2, representing 0.6% of the overall watershed. The most appropriate class is predominantly found in the stream channel in the central and downstream (southern) areas of the study watershed. The high suitability class (533.9 km^2 or 8.1%) is situated in the middle and southern areas of the watershed. The moderately suitable class covers an area of 1,675.5 km^2, representing 25.3% of the total. This class is evenly distributed across the entire watershed. The low and very low classes cover an area of 4,379.2 km^2 or 66.1% of the watershed. These classes are predominantly found in regions with extremely high elevations, specifically on hills ridges and peaks.

The factors that contribute to the presence class could be determined by comparing the DSI map with the different criterion layers. The areas classified as having very high and high suitability were characterized by high drainage density, high TWI and SI, second and higher stream order, low vegetation cover, moderate slope gradient, sandy clay loam soil texture, and normal temporal rainfall distribution in conjunction with igneous and sedimentary complex rock. These characteristics imply consistent and plentiful water flow for MHP operational continuity (Odiji *et al.,* 2021) and act as indicators of water availability, flow dynamics, runoff patterns, discharge characteristics, and potential energy generation (Korkovelos *et al.,* 2018). Higher TWI and SI values indicate higher flow accumulation and overland flow potential (Althuwaynee *et al.,* 2014). As the magnitude of the stream's order increases, a corresponding increase in discharge occurs while the gradient experiences a decrease (Sammartano *et al.,* 2019). High and very high suitability classes for MHP dam sites prioritize uninhabited or low vegetation cover areas due to minimal environmental effect associated with MHP projects in such areas, the cost-effectiveness of land obtaining, and the avoidance of significant effect on human activities (Ali *et al.,* 2023). A steeper slope results in increased runoff velocity and more water being generated, rendering the terrain more vulnerable to erosion and sediment transportation. Moderate to high slopes are particularly well-suited to the construction of MHP dam (Rahmati *et al.,* 2019). Regarding soil texture, fine to medium-textures are more suitable for MHP dam structures due to their significantly higher potential for water retention (Ibrahim *et al.,* 2019). High and very high suitability classes residing in a normal category of SPI value (-0.99 to 0.99) (Anshuka *et al.,* 2019) would guarantee consistent rainfall supply within the watershed's hydrological system, facilitating continuous drainage of existing rivers throughout the year (Reyes *et al.,* 2022). The igneous rocks under dam construction have a better bearing capacity, especially concerning the foundation being built and the ability of a dam to hold water (Zewdie and Tesfa, 2023). The primary elements that influence the moderately suitable class are normal rainfall spatial distribution, a fairly steep slope, and moderate drainage density, TWI, and SI. Regions characterized by low precipitation, steep slope gradient, fragile geological composition, and limited drainage density exhibit low and very low suitability zones. The result of this study regarding the characteristics of suitability classes are in line with those of other previous studies. Al-Ruzouq *et al.* (2019), who used integrated GIS and machine learning in dam site selection in the United Arab Emirates (UAE), found that the very high suitable zone for dams was characterized by adequate drainage and geological properties, such as relatively gentle slopes, geology dominated by sand, and high drainage density. Odiji *et al.* (2021), with their study conducted in Nigeria related to dam site suitability modeling, concluded that the area with high drainage density, high flow accumulation, gentle slope, moderate elevation, sufficient rainfall, basement complex rock, and low dense vegetation coverage exhibited high-level suitability. Othman *et al.* (2020), whose research theme was GIS-based modeling in the identification of check dam sites, defined the significant subfactors for check dam identification, consisting of hard rock for geology, clay loam soil texture, low vegetation coverage, moderate slope, and river with high potential flow.

Validation of the DSI map

The obtained DSI map was evaluated by comparing it with existing MHP dams in the study watershed, ensuring its accuracy. A total of 33 MHP dams exist in the study area for validation purposes (Fig. 6). The existing MHP dams are predominantly spread across

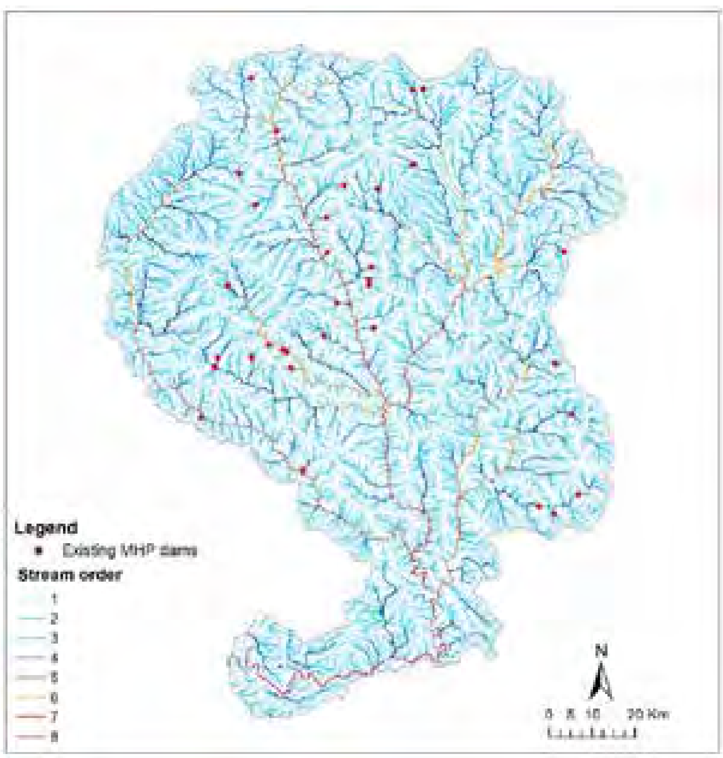

Fig. 6: Spatial distribution of existing MHP dams for validation

the central and upstream areas of the watershed, with a small proportion located in the eastern part. The model's performance in determining DSI was evaluated on the basis of the constructed ROC curve (Fig. 7). The prediction rate curve illustrates the model's capacity to make accurate predictions on the validation data. Based on Fig. 7, the AUC value was 0.919, indicating a satisfactory level of concurrence between the suitability index and the existing MHP dams. Several studies that showed good agreement between predicted and measured data were indicated by AUC values greater than 0.9, such as Yang *et al.* (2019) which studied landslide susceptibility mapping, Merghadi *et al.* (2020) which used machine learning application for landslide prediction, and Rahmati *et al.* (2019) which focused check dam site selection. Odiji *et al.* (2021), in their study of small hydropower dam site selection, obtained an AUC value of 0.8 in evaluating accuracy, indicating a strong correlation between the suitability map and existing dam data.

Characterization of existing MHP dams is also essential for defining potential MHP dam sites, particularly with respect to characteristics related to flow potential and socio-economic consideration (proximity from road and settlement). Fig. 8 presents the characteristic of existing MHP dams that are primarily situated in areas with high and very high suitability index classes, comprising 64% of the total dams, while 36% of existing MHP dams are in the moderate class. There are 52% of the dams located on the first and second stream orders, while 48% are on the third and fourth stream orders. The existing MHP dams are also primarily located within an area less than 4 km from road and settlement, accounting for 93% and 79%, respectively.

Potential site for MHP dam

The potential site for MHP dam was identified in accordance with several criteria: 1) potential flow and continuity; 2) the obtained DSI map; 3) the distance between two potential sites in the same stream; 4) the length of distinct MHP scheme; 5) potential hydraulic head; and 6) proximity from infrastructure and conservation forest. The approach used for identifying potential dam sites incorporated not only a hydrological point of view but also biophysical factors represented by DSI and socio-economic conditions. The preference of flow potential for potential MHP dam site was selected on the first and second order of stream. Nearly 50% of the existing MHP dams in the study area are located on the second order. This finding aligns with the study conducted by Sammartano *et al.* (2019) in South West England, which found that over 50% of the identified sites for MHP were situated in the first and second

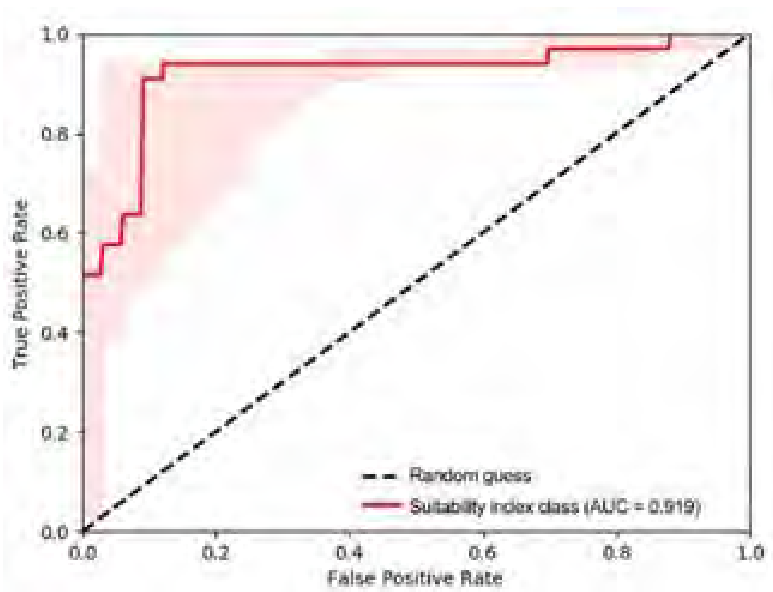

Fig. 7: The ROC for accuracy evaluation of suitability index mapping

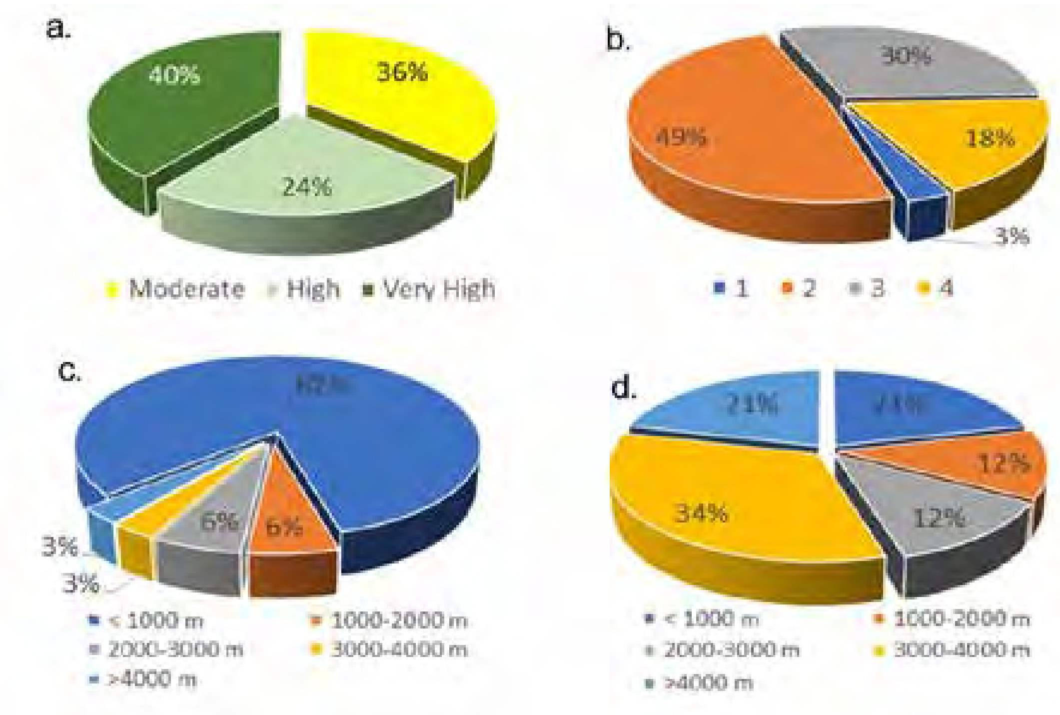

Fig. 8: Characteristic of existing MHP dams in the study area

stream order, with a subsequent drop in frequency as the stream order increased. High and very high suitability indices were considered for potential dam location selection. A distance of 500 m between two potential sites was the minimum spacing to prevent the interface of tailwater upstream and impoundment downstream (Moshe and Tegegne, 2022). A previous study suggested that the length of the distinct MHP scheme ranges from 500 m to 3,000 m (Pandey *et al.,* 2015). The current study used a 2,000 m radius of the single scheme MHP, assuming that it was sufficient for the MHP component, optimally regarding the cost of MHP development, and facilitating simple flow diversion. Several studies have proposed a hydraulic head threshold for MHP: 5 m (Mehari, 2020), 10 m (Rospriandana and Fujii, 2017), and 20 m (Pandey *et al.,* 2015). The current study defined the hydraulic head for MHP potential dam site as greater than 20 m. The potential dam location was also selected outside the conservation forest areas and less than 4,000 m from road and settlement. On the basis of all these conditions, overlay and query methods were used in the potential MHP dam selection. The identified potential sites for MHP dam are presented in Fig. 9.

The query operation of all the criteria identified 635 points as potential sites for MHP dams. These potential sites were predominantly distributed in the eastern part of the watershed, characterized by dense infrastructure, including roads and settlements. The high potential hydraulic head (>20 m) of the obtained dam sites would play an essential role in achieving higher potential power generation with relatively small to moderate river flow. The identified potential sites are also likely to feature a narrow valley, commonly found in the first and second stream orders. A narrow valley, particularly the V-shape, provides advantages with regard to dam structure and flow diversion, potentially reducing construction and operational costs, and possible effects on the environment (Odiji *et al.,* 2021).

Implication of the study result

Potential sites for the MHP dam map have numerous critical applications and uses in the context of harnessing water energy and managing large watersheds. Some of the essential applications

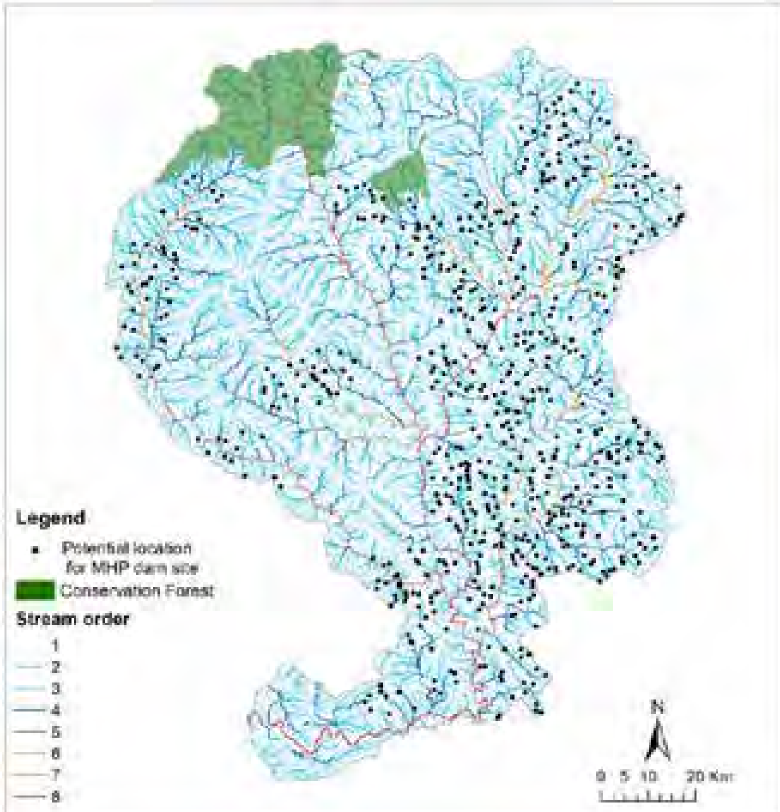

Fig. 9: Distribution of potential site for MHP dam in the study area

are as follows: 1) MHP dam site suitability mapping facilitates the identification of the most suitable locations for MHP dams based on biophysical, technical, and socio-economic factors, including water flow potential, geomorphometry, and proximity to existing infrastructure; 2) mapping assists in determining the potential energy that can be generated at each identified site to maximize the energy output while considering environmental and economic constraints; 3) dam site suitability mapping provides valuable insight into assessing the potential environmental impacts of constructing MHP dam, enabling the identification of sensitive areas that should be avoided or carefully managed, 4) understanding the suitability of sites within a watershed assists in the efficient management of water resources, and the allocation of water for energy production while ensuring other essential uses such as agriculture, drinking water supply, and ecological needs; 5) dam site suitability mapping results can inform policy decisions and planning processes related to renewable energy development, water resource management, and environmental protection; and 6) sharing dam suitability maps with local communities can promote transparency and facilitates communities' understanding of the potential benefits and drawbacks of MHP projects in their area, leading to better decision-making and collaboration. A more detailed investigation of potential sites is necessary to ensure the applicability of technical, biophysical, and socio-economical aspects. Various steps and consideration may be conducted by the government in implementing potential dam sites for MHP development. They include the following, 1) An environmental impact assessment will be carried out to evaluate potential effects on the ecosystem, wildlife, and local communities for formulating mitigation plans to minimize adverse effects; 2) Obtaining necessary permits and approvals from relevant authorities in compliance with environmental regulations, land rights, and any other legal requirements; 3) Engaging with local communities to address concerns, gather feedback, and ensure that the project is aligned with the community's needs and interests; 4) Once a site is selected and approvals are in placed, infrastructure development begins, including constructing dams, powerhouse structures, turbines, and other necessary facilities; 5) The government will employ suitable technology and engineering expertise to design and build the hydroelectric units efficiently and safely; 6) Post-construction, ongoing monitoring and maintenance are critical to ensure that the units operate effectively and safely while minimizing environmental impacts; 7) Establishing connections to the power grid enables the electricity generated to be distributed and utilized across the region. The approach developed in this study is a valuable tool for assessing potential dam sites for MHP projects, but it also has limitations: 1) Differences in the scale and resolution data used that can affect the performance of the model and increase the uncertainty aspect; 2) Complexity of variables in MHP development influence the criteria selection that can be challenging and may oversimplify the real-world scenario; and 3) Environmental conditions that are subject to change over time due to climate variations, land use alterations, or natural events, may not adequately account in approach development, affecting the long-term reliability of the suitability predictions. Supplementing the result of GIS-based suitability modeling with detailed field surveys, local knowledge, and detailed on-site assessments is essential. The results of this study also indicate only potential sites without information on potential power that can be generated. The measurement of dependable discharge through direct measurement or a modeling approach is critical because of the consequences, especially for a more detailed scale of analysis and location. Investigation of detailed soil properties is also essential in implementing the potential dam site for MHP development, especially related to dam structure.

CONCLUSION

The lack of an up-to-date national or sub-national/ regional inventory of potential dams' sites for MHP installation remains challenging in the midst of high dependency on fossil-based electricity and other global issues, such as climate change. This study has employed a comprehensive approach that utilized GIS-based suitability modeling to assess potential MHP dam sites in a large watershed. The integration of various geospatial data layers, including geomorphometry, geology, rainfall, soil texture, and LULC, allows for a robust analysis of DSI mapping. The potential sites for the MHP dams were obtained by incorporating the MHP DSI map with socio-economic factors (proximity distance from road and settlement), conservation forest areas, and potential hydraulic head. Using the Saddang watershed as the study location, the DSI map was obtained and divided into five suitability classes. High and very high categories of the suitability index constituted 8.7% of the study area. These areas were characterized by high TWI, drainage density, and SI, low vegetation cover, moderate slope, located on the second or higher stream orders, normal rainfall temporal distribution, sandy clay loam soil texture, and igneous and sedimentary complex rock. A total of 635 potential MHP dam sites were resulted from overlay and query processes on the basis of several criteria: high and very high DSI, first and second stream order, outside conservation forest areas, less than 4,000 m from road and settlement, and greater than 20 m of potential hydraulic head. The results of this study provide valuable insights for decision-makers, enabling them to make informed choices regarding MHP dam site selection for further detailed measurement of the targeted site. The methodology presented herein can serve as a valuable framework for future MHP project planning, not only in the studied watershed but also in similar regions worldwide in the context of large watersheds or at national/ province level. The insights gleaned from this study are also expected to pave the way for more efficient and ecologically sound approaches to harness the immense potential of MHP resources. More detailed field surveys, local knowledge, and detailed on-site assessments are essential for supplementing GIS modeling in future work. Integrating GIS with other decision-making tools and involving stakeholders at various stages of site selection can help mitigate this study's limitations and produce more reliable and comprehensive results for MHP dam site suitability.

AUTHOR CONTRIBUTIONS

All Authors made equal contributions as the main contributors. O. Setiawan conducted the research conceptualization, literature review, data collection, spatial data preparation, analysis and interpretation of results, and draft manuscript preparation. H.Y.S.H. Nugroho conducted the research conceptualization, the interpretation of results, and draft manuscript editing and review. N. Wahyuningrum conducted the interpretation of results, draft manuscript editing, and review. D. Auliyani prepared and analyzed spatial data, interpreted analysis results, and edited and reviewed the draft manuscript. K.S. Hardjo. analyzed the data and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

ABBREVIATIONS

%	Percent
o	Degree
'	Minute
"	Second
β	Slope gradient
λ_{max}	Maximum eigenvalue
σ	Standard deviation
A	Area
AHP	Analytical Hierarchy Process
AUC	Area under the curve
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CI	Consistency index
CO_2	carbon dioxide
CR	Consistency Ratio
Dd	Drainage density
DEM	Digital elevation model
DSI	Dam suitability index
E	East
GW	Giga watt
GIS	Geographic information systems
ha	Hectare
km	Kilometer
km^2	Square kilometer
LULC	Land use land cover
m	Meter
MCDM	Multi-criteria decision-making
MHP	Micro hydropower plant
mm	Second
RCI	Random consistency index
ROC	Receiver operating characteristic
RS	Remote sensing
S	South
SI	Stream power index

SPI	Standardized precipitation index
TWI	Topographic wetness index
UAE	United Arab Emirates
WSM	Weighted sum method
xi	Monthly rainfall
$\bar{x}$	Average monthly rainfall

REFERENCES

Abdulkareem, J.H.; Pradhan, B.; Sulaiman, W.N.A.; Jamil, N.R., (2019). Long-term runoff dynamics assessment measured through land use/cover (LULC) changes in a tropical complex catchment. Environ. Syst. Dec., 39(1): 16–33 (**18 pages**).

Ajibade, T.F.; Nwogwu, N.A.; Ajibade, F.O.; Adelodun, B.; Idowu, T.E.; Ojo, A.O.; Iji, J.O.; Olajire, O.O.; Akinmusere, O.K., (2020). Potential dam sites selection using integrated techniques of remote sensing and GIS in Imo State, Southeastern, Nigeria. Sustainable Water Resour. Manage., 6(4): 57-72 (**16 pages**).

Ali, S.; Stewart, R.A.; Sahin, O.; Vieira, A.S., (2023). Integrated GIS-AHP-based approach for off-river pumped hydro energy storage site selection. Appl. Energy., 337:120914 (**19 pages**).

Allafta, H.; Opp, C.; Patra, S., (2021). Identification of groundwater potential zones using remote sensing and GIS techniques: A case study of the shatt Al-Arab Basin. Remote Sens., 13(1): 1–28 (**28 pages**).

Al-Ruzouq, R.; Shanableh, A.; Yilmaz, A.G.; Idris, A.E.; Mukherjee, S.; Khalil, M.A.; Gibril, M.B.A., (2019). Dam site suitability mapping and analysis using an integrated GIS and machine learning approach. Water. 11(9):1-17 (**17 pages**).

Althuwaynee, O.F.; Pradhan, B.; Park, H.J.; Lee, J.H., (2014). A novel ensemble bivariate statistical evidential belief function with knowledge-based analytical hierarchy process and multivariate statistical logistic regression for landslide susceptibility mapping. Catena. 114: 21–36 (**16 pages**).

Andualem, T.G.; Hagos, Y.G.; Kefale, A.; Zelalem, B., (2020). Soil erosion-prone area identification using multi-criteria decision analysis in Ethiopian highlands. Model. Earth Syst. Environ., 6(3): 1407–1418 (**12 pages**).

Anshuka, A.; van Ogtrop, F.F.; Willem Vervoort, R., (2019). Drought forecasting through statistical models using standardised precipitation index: a systematic review and meta-regression analysis. Nat. Hazard., 97(2): 955–977 (**23 pages**).

Avtar, R.; Sahu, N.; Aggarwal, A.K.; Chakraborty, S.; Kharrazi, A.; Yunus, A.P.; Dou, J.; and Kurniawan, T.A., (2019). Exploring renewable energy resources using remote sensing and GIS-A review. Resour., 8(3): 1-23 (**23 pages**).

Bayazıt, Y.; Bakış, R.; Koç, C., (2017). An investigation of small scale hydropower plants using the geographic information system. Renewable Sustainable Energy Rev., 67: 289–294 (**6 pages**).

Frimawaty, E.; Ilmika, A.; Sakina, N.A; Mustabi. J., (2023). Climate change mitigation and adaptation through livestock waste management. Global J. Environ. Sci. Manage., 9(4): 691-706 (**16 pages**).

Funk, C.; Peterson, P.; Landsfeld, M.; Pedreros, D.; Verdin, J.; Shukla, S.; Husak, G.; Rowland, J.; Harrison, L.; Hoell, A.; and Michaelsen, J., (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Sci. Data, 2: 1-21 (**21 pages**).

García, A.M.; Díaz, J.A.R.; Morillo, J.G.; McNabola, A., (2021). Energy recovery potential in industrial and municipal wastewater networks using micro-hydropower in Spain. Water, 13: 691 (**14 pages**).

Gidey, E.; Dikinya, O.; Sebego, R.; Segosebe, E.; Zenebe, A., (2018). Modeling the spatio-temporal meteorological drought characteristics using the Standardized Precipitation Index (SPI) in Raya and Its Environs, Northern Ethiopia. Earth Syst. Environ., 2: 281–292 (**12 pages**).

Hammid, A.T.; Sulaiman, M.H.B.; Abdalla, A.N., (2018). Prediction of small hydropower plant power production in Himreen Lake dam (HLD) using artificial neural network. Alexandria Eng. J., 57: 211–221 (**11 pages**).

Harjanne, A.; Korhonen, J.M., (2019). Abandoning the concept of renewable energy. Energy Policy. 127: 330–340 (**11 pages**).

Hojati, M.; and Mokarram, M., (2016). Determination of a Topographic Wetness Index using high resolution digital elevation models. Eur. J. Geogr., 7(4): 41-52 (**12 pages**).

Ibrahim, G.R.F.; Rasul, A.; Hamid, A.A.; Ali, Z.F.; Dewana, A.A., (2019). Suitable site selection for rainwater harvesting and storage case study using Dohuk governorate. Water, 11(864): 1-16 (**16 pages**).

Irmayani, I.; Putera, M.I.; Alam, S.; Surahman, S.; Masnur, M., (2018). Land use potential on water balance based on SWAT method in Saddang Watershed in Bendung Benteng Irrigation System. Agrotech. J., 3(2): 53–60 (**8 pages**).

Korkovelos, A.; Mentis, D.; Siyal, S.H.; Arderne, C.; Rogner, H.; Bazilian, M.; Howells, M.; Beck, H.; De Roo, A., (2018). A geospatial assessment of small-scale hydropower potential in sub-saharan Africa. Energies, 11: 1-21 (**21 pages**).

Lamada, M.S.; Moh Ahsan Mandra ST, M.S.; Andi Makkawaru Isa Zarni Jassin, M., (2022). Morfometri, perubahan penggunaan lahan, zonasi dan pemodelan banjir Daerah Aliran Sungai (DAS) Saddang and Mata Allo Kabupaten Enrekang, Sulawesi Selatan. Media Nusa Creative publisher. Malang, Indonesia. (**298 pages**).

Lee, H.C.; Chang, C.T., (2018). Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. Renewable Sustainable Energy Rev., 92: 883–896 (**13 pages**).

Livada, I.; Assimakopoulos, V.D., (2007). Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). Theor. Appl. Climatol., 89: 143–153 (**11 pages**).

Mehari, K.A., (2020). GIS based assessment of hydropower potential (A case study on Gumara river basin). Am. Sci. Res. J Eng. Technol. Sci., 69(1): 26–44 (**18 pages**).

Meles, M.B.; Younger, S.E.; Jackson, C.R.; Du, E.; Drover, D., (2020). Wetness index based on landscape position and topography (WILT): Modifying TWI to reflect landscape position. J. Environ. Manage., 255, 109863 (**9 pages**).

Merghadi, A.; Yunus, A.P.; Dou, J.; Whiteley, J.; ThaiPham, B.; Bui, D.T.; Avtar, R.; Abderrahmane, B., (2020). Machine learning methods for landslide susceptibility studies: A comparative overview of algorithm performance. Earth Sci. Rev., 207: 103225 (**47 pages**).

Ministry of Environment and Forestry, (2020). The state of the Indonesia’s forests 2020. Kementerian Lingkungan Hidup dan Kehutanan, Jakarta, Indonesia. (**118 pages**).

Ministry of Forestry, (2014). Statistik Kawasan Hutan 2013. Ministry of Forestry, Jakarta, Indonesia. (**131 pages**).

Mohammady, M.; Pourghasemi, H.R.; Amiri, M., (2019). Land subsidence susceptibility assessment using random forest machine learning algorithm. Environ. Earth Sci., 78: 503 (**12 pages**).

Moran, E.F.; Lopez, M.C.; Moore, N.; Müller, N.; Hyndman, D.W., (2018). Sustainable hydropower in the 21st century. Proceedings of the National Academy of Sciences of the United States of America, 115(47): 11891–11898 (**8 pages**).

Moshe, A.; Tegegne, G., (2022). Assessment of run-of-river hydropower potential in the data-scarce region, Omo-Gibe Basin, Ethiopia. Int. J. Energy Water Resour., 6: 531–542 (**12 pages**).

Odiji, C.; Adepoju, M.; Ibrahim, I.; Adedeji, O.; Nnaemeka, I.; Aderoju, O., (2021). Small hydropower dam site suitability modelling in upper Benue river watershed, Nigeria. Appl. Water Sci., 11: 136 (**17 pages**).

Olabi, A.G.; Abdelkareem, M.A., (2022). Renewable energy and climate change. Renewable Sustainable Energy Rev., 158: 112111 (**7 pages**).

Othman, A.A.; Al-Maamar, A.F.; Al-Manmi, D.A.M.A.; Liesenberg, V.; Hasan, S.E.; Obaid, A.K.; Al-Quraishi, A.M.F., (2020). GIS-based modeling for selection of dam sites in the Kurdistan Region, Iraq. ISPRS Int. J. Geo-Inf. , 9: 244 (**34 pages**).

Owolabi, S.T.; Madi, K.; Kalumba, A.M.; and Orimoloye, I.R., (2020). A groundwater potential zone mapping approach for semi-arid environments using remote sensing (RS), geographic information system (GIS), and analytical hierarchical process (AHP) techniques: a case study of Buffalo catchment, Eastern Cape, South Africa. Arabian J. Geosci., 13(1184): 1–17 (**18 pages**).

Pandey, A.; Lalrempuia, D.; Jain, S.K., (2015). Assessment of hydropower potential using spatial technology and SWAT modelling in the Mat River, southern Mizoram, India. Hydrol. Sci. J., 60(10): 1651–1665 (**15 pages**).

Papangelakis, E.; MacVicar, B.; Ashmore, P.; Gingerich, D.; Bright, C., (2022). Testing a Watershed-scale stream power index tool for erosion risk assessment in an urban river. J. Sustainable Water Built Environ., 8(3): 1-14 (**14 pages**).

Pham, B.T.; Prakash, I., (2018). Machine learning methods of kernel logistic regression and classification and regression trees for landslide susceptibility assessment at part of Himalayan Area, India. Indian J. Sci. Technol., 11(12): 1–10 (**10 pages**).

Pottmaier, D.; Melo, C.R.; Sartor, M.N.; Kuester, S.; Amadio, T.M.; Fernandes, C.A.H.; Marinha, D.; Alarcon, O.E., (2013). The Brazilian energy matrix: From a materials science and engineering perspective. Renewable Sustainable Energy Rev., 19: 678–691 (**14 pages**).

Rahayu, L.N.; Windarta, J., (2022). Tinjauan potensi dan kebijakan pengembangan PLTA dan PLTMH di Indonesia. Jurnal Energi Baru Dan Terbarukan, 3(2): 88–98 (**11 pages**).

Rahmati, O.; Kalantari, Z.; Samadi, M.; Uuemaa, E.; Moghaddam, D.D.; Nalivan, O.A.; Destouni, G.; Bui, D.T., (2019). GIS-based site selection for check dams in watersheds: Considering geomorphometric and topo-hydrological factors. Sustainability. 11(5639): 1-20 (**20 pages**).

Reyes, L.J.C.; Rangel, H.Á.; Herazo, L.C.S., (2022). Adjustment of the Standardized Precipitation Index (SPI) for the Evaluation of Drought in the Arroyo Pechelín Basin, Colombia, under Zero Monthly Precipitation Conditions. Atmosphere. 13, 236: 1-13 (**13 pages**).

Rospriandana, N.; Fujii, M., (2017). Assessment of small hydropower potential in the Ciwidey subwatershed, Indonesia: A GIS and hydrological modeling approach. Hydrol. Res. Lett., 11(1): 6–11 (**6 pages**).

Roy, D.P.; Wulder, M.A.; Loveland, T.R.; Woodcock, C.E.; Allen, R.G.; Anderson, M.C.; Helder, D.; Irons, J.R.; Johnson, D.M.; Kennedy, R.; Scambos, T.A.; Schaaf, C.B.; Schott, J.R.; Sheng, Y.; Vermote, E.F.; Belward, A.S.; Bindschadler, R.; Cohen, W.B.; Gao, F.; Hipple, J.D.; Hostert, P.; Huntington, J.; Justice, C.O.; Kilic, A.; Kovalskyy, V.; Lee, Z.P.; Lymburner, L.; Masek, J.G.; McCorkel, J.; Shuai, Y.; Trezza, R.; Vogelmann, J.; Wynne, R.H.; Zhu, Z., (2014). Landsat-8: science and product vision for terrestrial global change research. Remote Sens. Environ., 145: 154-172 (**19 pages**).

Saaty, T.L., (2008). Decision making with the analytic hierarchy process. Int. J. Serv. Sci., 1(1): 83-98 (**16 pages**).

Samimi, M.; Moghadam, H., (2024). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustain. Energy Rev., 190: 113969 (**10 pages**).

Sammartano, V.; Liuzzo, L.; Freni, G., (2019). Identification of potential locations for run-of-river hydropower plants using a GIS-based procedure. Energies. 12, 3446: 1-20 (**20 pages**).

Sihombing, F.M.H.; Sahdarani, D.N.; Supriyanto, (2021). DEMNAS: a recently released nation-wide digital elevation model from the Indonesian Government and its implication for geothermal exploration – study case of Gunung Endut Geothermal Prospect, Banten Province, Indonesia. In Proceedings World Geothermal Congress. Reykjavik, Iceland April – October. International Geothermal Association: The Hague (**11 pages)**.

Sissakian, V.K.; Adamo, N.; Al-Ansari, N., (2020). The role of geological investigations for dam siting: Mosul dam a case study. Geotech. Geol. Eng., 38: 2085–2096 (**12 pages**).

Stepanov, A.S.; Kalina, R.A.; Stepanova, A.A., (2016). Analysis of power and energy loss based on long line equations. Russ. Electr. Eng., 87(7): 390–394 (**5 pages**).

Villeneuve, M.; Gunawan, W.; Cornee, J. J.; and Vidal, O., (2002). Geology of the central Sulawesi belt (eastern Indonesia): Constraints for geodynamic models. Int. J. Earth Sci., 91(3): 524–537 (**14 pages**).

Wahyuono, R.A.; and Julian, M.M., (2018). Revisiting Renewable Energy Map in Indonesia: Seasonal Hydro and Solar Energy Potential for Rural Off-Grid Electrification (Provincial Level). MATEC Web of Conferences. 164: 1-11 (**11 pages**).

Yang, J.; Song, C.; Yang, Y.; Xu, C.; Guo, F.; Xie, L., (2019). New method for landslide susceptibility mapping supported by spatial logistic regression and GeoDetector: A case study of Duwen Highway Basin, Sichuan Province, China. Geomorphology, 324: 62–71 (**10 pages**).

Yu, Y.; Zhu, R.; Ma, D.; Liu, D.; Liu, Y.; Gao, Z.; Yin, M.; Bandala, E.R.; Rodrigo-Comino, J., (2022). Multiple surface runoff and soil loss responses by sandstone morphologies to land-use and precipitation regimes changes in the Loess Plateau, China. Catena. 217: 1-10 (**10 pages**).

Zewdie, M.M.; Tesfa, C., (2023). GIS-based MCDM modeling for suitable dam site identification at Yeda watershed, Ethiopia. Arabian J. Geosci., 16: 1-26 (**26 pages**).

Zhao, B.; Zhang, L.; Xia, Z.; Xu, W.; Xia, L.; Liang, Y.; Xia, D., (2019). Effects of Rainfall Intensity and Vegetation Cover on Erosion Characteristics of a Soil Containing Rock Fragments Slope. Adv. Civ. Eng., 2019: 1-14 (**14 pages**).

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CASE STUDY

Decarbonizing gas emissions from petrochemical production using microalgae

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ABSTRACT

BACKGROUND AND OBJECTIVES: Greenhouse gas emissions are the primary cause of global warming. Under the Paris Agreement, all countries have developed programs to reduce anthropogenic impact on the environment. In the petrochemical industry, for example, isoprene, is a major contributor to the production of carbon dioxide, generating large amounts of acidic and hydrocarbon gases that are burned and released into the atmosphere. This study aimed to investigate the absorption of greenhouse gases from isoprene production by the marine microalgae Isochrysis galbana and Tetraselmis suecica, as well as the freshwater microalgae Chlorella vulgaris.

METHODS: Microalgae cells were cultured in a bioreactor. The grown microalgae strains and mineralized water were fed to the bioreactor. Gases discharged from isoprene production were passed through the bioreactor. Inlet and outlet gas compositions were monitored by chromatography.

FINDINGS: Absorption of gases discharged from isoprene production by microalgae was studied for the first time. Chlorella vulgaris microalgae reduced methane and carbon dioxide contents by an average of 20 times. A mixture of microalgae Tetraselmis suecica and Isochrysis galbana reduced methane and carbon dioxide contents by a factor of 10 but completely absorbed hydrocarbon gases from methane to pentane.

CONCLUSION: The results indicate that microalgae cultivation can be used as a reliable and stable technology for the biofixation of the gases discharged in isoprene production. This technology can eliminate the combustion stage of hydrocarbon gases in isoprene production and significantly reduce carbon dioxide emissions into the atmosphere.

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INTRODUCTION

Anthropogenic blow-off gases emitted into the atmosphere by industrial and energy enterprises significantly increase the amount of greenhouse gases. The greenhouse gas used to record the emissions of fossil fuel combustion products into the atmosphere is carbon dioxide (CO_2). The emissions of CO_2 determine the amount of greenhouse gases according to the Kyoto Protocol and other agreements. According to numerous studies and obtained technical solutions (Mitsubishi Heavy Ind. Ltd., 1991; Yilong *et al*., 2015), the concentration of CO_2 in the atmosphere has already exceeded 420 ppm in April 2021. The International Group of Experts on Climate Change predicts that by 2100, CO_2 concentrations will reach 570 ppm, leading to an increase in the average temperature of the Earth's surface by 1.9 degrees Celsius (°C) (Dissanayake *et al*., 2019). It has been reported (Li *et al*., 2023) that about 60 percent (%) of the Earth's inhabitants experience record-high annual temperatures. Excessive CO_2 emissions are generally considered the primary cause of global warming. Moreover, CO_2 emissions account for about 80% of all greenhouse gases. Human activities are the main cause of CO_2 emissions into the atmosphere, with fossil fuel combustion, agricultural activities, and industrial processes (Hussain *et al*., 2018) playing a leading role. In particular, since the Industrial Revolution, the use of fossil fuels in the power generation sector has been the main source of CO_2 emissions (Ahmed *et al*., 2019). The Paris Agreement on reducing greenhouse gas emissions has been signed by most countries. Microalgae are a good choice for use in the biological capture of CO_2 and other greenhouse gases because they are universal photosynthetic microorganisms and, most importantly, can capture the heat and fine dust emitted by blow-off and exhaust gases (Kamyab *et al.,* 2019). The high emissions in the Northern Hemisphere are due to the large number of industrial establishments in Eurasia and North America. Moreover, large populations and big-scale transportation systems consume significant amounts of energy in this part of the world. There is another important factor, which is the climatic specialties of the regions that require a long heating season. In addition, climate affects all aspects of people's lives, including energy consumption (Arredondo, 2023), the efficiency of machinery, and industry in general (Farajzadeh, 2023). Anthropogenic blow-off gas emitted by industrial and energy enterprises significantly increases the amount of greenhouse gases in the atmosphere. These greenhouse gases include carbon oxides, water vapor, sulfur oxides, nitrogen oxides, polycyclic aromatic hydrocarbons, fluoride compounds, and solid particles (Laptev *et al*., 2022). Currently, several methods have been proposed for the disposal of carbon dioxide. Some of these methods have been successfully implemented. An example is the possibility of using compressed carbon dioxide as dry ice. However, this technology cannot be fully utilized as CO_2 returns to the atmosphere during its use (De Morais *et al*., 2007). Other methods of CO_2 waste utilization include a variety of physicochemical methods; however, the main problem common to all options is the cost of CO_2 absorption technology. Absorption, transportation, and storage of CO_2 are very costly, thus undermining the cost-effectiveness of the projects. Currently, the biological absorption of CO_2 through photosynthesis using Chlorella vulgaris is the only promising method. One way to reduce CO_2 levels is by passing the exhaust gases through photobioreactors containing microalgae (Aryal *et al*., 2021). The vital role and main life activity of microalgae is photosynthesis, during which the microalgae consume CO_2 and solar radiation energy. In addition, the biomass remaining during and after cultivation can be used for the biotechnological production of biofuels, fertilizers, etc (Samimi *et al.,* 2023). Microalgae are a promising source of biomass thanks to their fast reproductive rates. They can produce up to 70 tons per hectare per year (t/ha/y) of biomass when using open ponds (even though poplar biomass is 10–13 t/ha/y) (Balagurumurthy *et al*., 2013). An important characteristic of microalgae is that they do not require land cultivation or significant expenditure on freshwater (either salt-rich water or wastewater can be used). Furthermore, they can absorb significant amounts of CO_2 (Culaba *et al*., 2020). Microalgae have been found to have the highest CO_2 fixation efficiency compared to terrestrial plants (Cheah *et al*., 2015). This can be explained by the faster rate at which substances are transported through algal cell membranes (Zeng *et al*., 2012) than through plant capillaries, rapid metabolism, and cell division (on average, each cell divides once a day), and the ability of unicellular organisms to mutate and adapt to environmental conditions (Chen *et* *al*., 2013). Microalgae have been shown to capture approximately 1.8 kilogram (kg) of carbon dioxide per kilogram of microalgae (kg-CO_2/1 kg) of biomass produced. Microalgae biomass is a source of lipids and carbohydrates (CHO) and is a production material for alternative motor fuels (biodiesel and bioethanol) (Culaba *et al*., 2020), hydrogen (H_2), propylene glycol (Otsuka, 1961), formic acid, cosmetics, and some other products (Arenas *et al*., 2016). The combination of biotechnological and catalytic processes to obtain such products is carried out in the bioprocessing of complex plant materials (Gong *et al*., 2014; Samimi and Nouri, 2023). Taking these into account, microalgae cultivation technology can be used to absorb blow-off gases to obtain useful by-products and minimize greenhouse gas, heat, and dust emissions into the atmosphere (Slegers *et al*., 2020). The main objective of this research was to use microalgae culture to develop industrial blow-off gas utilization technology in order to reduce CO_2 emissions. This technology can significantly reduce greenhouse gas emissions from the petrochemical industry, hence reducing anthropogenic impact on the environment. This work studied the absorption capacity of the marine microalgae Tetraselmis suecica and Isochrysis galbana, as well as the freshwater Chlorella vulgaris during gas purification from the catalytic processing of isoprene petrochemical production from CO_2-containing impurities of methane (CH_4) and other hydrocarbon gases. This study aimed to investigate the absorption of greenhouse gases from isoprene production by the marine microalgae Isochrysis galbana and Tetraselmis suecica, as well as the freshwater microalgae Chlorella vulgaris.The study was conducted in 2023 at the Ufa State Petroleum Technical University in Ufa, Republic of Bashkortostan, Russia.

MATERIALS AND METHODS

According to the literature (Cho *et al*., 2020; Deamici *et al*., 2019; Duarte *et al*., 2016), decarbonizing blow-off gases and exhaust gases of oil refineries using microalgae strains in laboratory conditions is typically based on creating a gas model and selecting a narrow range of carbon dioxide concentration in an inert solvent medium. In turn, in actual production conditions, the contents of CO_2 and hydrocarbon gases in the discharged gases change, affecting the microalgae absorption properties. Isochrysis galbana, Tetraselmis suecica, and Chlorella vulgaris are widely used as experimental subjects, having passed the stages of pilot testing and being applied in practice. Thus, these species were chosen to investigate their CO_2 absorption capacity in blow-off gases that contain the components of methane series ranging from C_1 to C_5. Isochrysis galbana is a marine microalga used in the aquaculture industry (Coutinho *et al*., 2006). This microalga is characterized by high division rates and lipid accumulation, leading to high lipid productivity and a significant increase in valuable chemicals such as omega-3 fatty acids. In addition, Bhatti *et al*. (2002) reported that Isochrysis galbana assimilates carbon by the active transfer of CO_2 and bicarbonate ions (HCO_3^-) through expressing a coenzyme carbonic anhydrase. Tetraselmis suecica is a marine green alga belonging to the prasinophytes and is widely used in hatcheries as food for bivalves, shrimp larvae, and rotifers (Muller-Feuga, 2004). It is also produced on an industrial scale for sale in the aquaculture market (Tredici *et al*., 2009). These marine microalgae present a wide range of antimicrobial properties (Austin *et al*., 1990; Austin *et al*., 1992) and have high potential as probiotics for fish (Irianto *et al*., 2002). Due to the high content of vitamin E, Tetraselmis suecica is also used as a source of this vitamin for humans and animals (Carballo-Cárdenas *et al*., 2003). Chlorella vulgaris with well-studied morphological and physiological characteristics is widely used as an experimental subject (Bajguz *et al*., 2009). Chlorella vulgaris is a cosmopolitan species that inhabits both terrestrial and aquatic environments: freshwater and saltwater. Chlorella vulgaris can obtain energy to develop through photosynthesis (autotrophic method) and respiration process (heterotrophic method). In addition, Chlorella vulgaris can combine the two methods (mixotrophic method) (Masojídek *et al*., 2014). This strain has been extensively studied, used in several industrial experiments, and found to be a fast-growing strain with the ability to capture CO_2 from blow-off gases (Van Den Hende, 2012). It is rich in proteins (51%–58%), carbohydrates (12–17%) and lipids (14–22%) (Cheah *et al*., 2015). To study the ability of microalgae to absorb emission gas components free of harmful sulfur oxides and nitrogen oxides, the gases formed during the dehydrogenation of isopentane into isoprene were selected. The content of sulfur and nitrogen compounds was strictly regulated, ensuring their absence in the exhaust gas. The exhaust gases from isoprene production were fed into a cooling system to reach a temperature of 45–55 °C to purify it from catalytic dust. The gases were then fed into a burner for combustion. Currently, the gases discharged in this way are released into the atmosphere. The experimental gas was selected before the burner. The gas was extracted into a rubber cylinder and delivered to the laboratory. The appearance of methane in blow-off gases during intermediate selections from the tap position 5. Fig. 1 shows the adaptation of microorganisms to the nutrient medium and the formation of microalgae methane-forming bacterial symbiotes. Marine microalgae strains were provided by the Department of Materials Science and Corrosion Protection, Ufa State Petroleum Technical University, Russia. Cells were cultured in silicate-free mineralized-33 g/L (Guillard, 1975) enriched artificial seawater. In each experiment conducted as part of this study, microalgae underwent two successive growth stages: a preparation stage and a cultivation stage. In the preparation stage, cells were periodically multiplied in 500-mL Erlenmeyer flasks containing 250 mL of solution and then transferred to 3-L Erlenmeyer flasks containing 1.75 L of solution. Cultivation flasks were maintained at 25°C, a photoperiod of 12:12 hours (h), and a light intensity of 70 squre meter per second (m^2/s) under fluorescent lamps. The 500-mL Erlenmeyer flasks underwent the process of barbotage by blowing filtered air through an aquarium compressor at an airflow rate of 800 cm^3/min. These algal cultures were used as starter cultures in the late exponential growth phase of the cultivation stage in a laboratory photobioreactor. The scheme of the photobioreactor is shown in Fig. 1.

Method of the gas composition analysis - In the exhaust gas, the volume fractions of non-hydrocarbon gases, such as H_2, nitrogen (N_2), oxygen (O_2) carbon monoxide (CO), CO_2, and methane, were determined through absolute calibration using the LHM-8MD gas chromatograph with a flame ionization detector. The gas chromatograph is equipped with a chromatograph control unit and a chromatograph information processing unit. The chromatographic column was 2-m long and 3–4 mm internal diameter. Molecular sieve zeolite NaX (fraction 0.25–0.5 mm) was calcined at T = 300°C. The mass fractions of C_2–C_5 hydrocarbons were measured in the same gas chromatograph equipped with a thermal conductivity detector, a chromatographic column of 6-m length, and 3–4 mm internal diameter. The liquid phase was triethylene glycol dibutylate, and diatomite was used as the solid carrier. The method for the continuous cultivation mode on gas absorption experiments was based on existing production methods. Gas bubbling was performed sequentially through a cascade of 4 flasks passing through a layer of microalgae suspension. To obtain isoprene dehydrogenation of isopentane, the experiments were conducted using waste gas from petrochemical production. The bioreactor consisted of seven 3-L Erlenmeyer flasks with the gas supply tube down, to each flask was added 10–14 mL microalgae suspension, and the height of the liquid column was 10 cm. The tests were conducted during the daytime. Cylinders were placed at the inlet of the first four flasks and the outlet of the last four flasks (Fig. 1). Gas from storage tank 1 was pumped by peristaltic pump 2 at a flow rate of 200 mL/min. After the gas was completely pumped from cylinders 1 to 6 (1 run), they were rearranged, and bubbling continued. Gas sampling for component

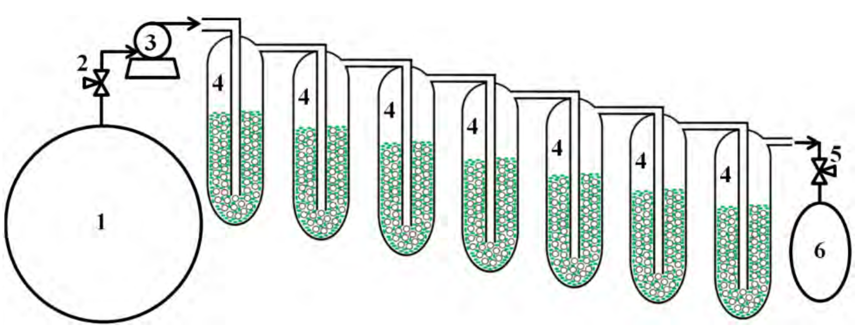

Fig. 1: Schematic of the bioreactor: 1- Cylinder with discharged gases, 2- Intake valve, 3- Peristaltic pump, 4- three-liter Erlenmeyer flasks containing microalgae, 5- Sampling outlet, 6- Intake cylinder.

Table 1: Changes in the composition of blow-off gas components before and after passing through the photobioreactor

Product	Cell	Cell volume, (cm^3)	Components composition (wt.%)															
			H_2	O_2	N_2	CH_4	CO	CO_2	Ethane	Propa-ne	Propy-lene	Isobut-ane	Butane	α-isobu-tane	β-trans-butan	β-trans-butan	Isopen-tane	Neopen-tane
Initial blow-off gas	before	57	15.43	0.375	42.13	24.66	2.47	2.42	6.97	2.45	2.68	0.241	0,0018	0,15	0	0,021	0,0034	0,0015
Blow-off passed through barboters with	after 7 runs	53	16.05	1.07	49.54	23.98	1.38	1.34	3.98	1.20	1.30	0.106	0,00057	0,064	0	0,0071	0,0011	0,0007
marine microalgae Tetraselmis suecica	after 24 h	55	0.934	27.75	70.82	0	0	0.105	0.38	0	0.0061	0.0007	0	0,00075	0	0,00048	0	0
Initial blow-off gas	before	57	15.43	0.375	42.13	24.66	2.47	2.42	6.97	2.45	2.68	0.241	0,0018	0,15	0	0,021	0,0034	0,0015
Blow-off passed through barboters with	after 7 runs	52	17.02	0.61	47.52	27.46	1.97	1.07	2.69	0.767	0.782	0.071	0,00018	0,036	0	0,0042	0	0,0001
marine microalgae Isochrysis galbana	after 24 h	54	0.96	30.35	67.30	0	0	0.104	1.28	0	0.0034	0.00053	0	0,00063	0	0,00041	0	0
Initial blow-off gas	before	50	11.1	8.2	42.36	18.19	1.09	1.84	7.61	2.81	3.02	0.694	0,182	2,57	0,018	0,025	0,18	0,103
Blow-off passed through barboters with	after 7 runs	54	15.28	0.38	39.66	30.54	2.11	1.46	4.91	1.87	1.88	0.416	0,081	1,26	0,0079	0,010	0,074	0,063
marine microalgae Tetraselmis suecica and Isochrysis galbana	after 24 h	55	1.28	29.94	67.10	0.28	0	0.16	1.23	0	0	0	0	0,0018	0	0	0	0

composition analysis was performed from cylinders 1 to 6 (Fig. 1).

RESULTS AND DISCUSSION

The CO_2 absorption efficiency for both microalgae species was 95.0% (Table 1). The marine microalgae Tetraselmis suecica and Isochrysis galbana showed the greatest affinity for hydrocarbons of the C_1–C_5 methane series. Moreover, the residual concentration of the gases at the outlet of the photobioreactor decreased completely as the number of carbon atoms in the chain increased. Assuming that the C_1–C_5 gases are components of the nutrient medium of the algal strains under study, the practical implementation of CO_2 absorption in production excludes the operation of flaring of these gases and further reduces CO_2 and water vapor emissions into the atmosphere. After 1 day, the total nitrogen and oxygen concentrations in the gas volume of the receiving chamber increased significantly from 42.51–48.13 weight percent (wt.%) to 97.65–98.57 wt.%. To simultaneously study the CO_2 absorption efficiency of the two algal strains, additional blow-offs were selected, hence the composition of the source gas was slightly different. The CO_2 absorption capacity of the microalgae mixture was 91.3%. A similar dependence was obtained for the absorption of hydrocarbons of the C_1–C_5 methane series by the mixture of algal strains. After 1 day, the gas volume in the receiving chamber showed a significant increase of 97.04 wt.% in the total percentage of nitrogen and oxygen. These results indicate that the use of strains of marine microalgae Tetraselmis suecica and Isochrysis galbana is a promising method for capturing CO_2 and C_1–C_5 methane series hydrocarbons in the blow-off gases of petrochemical and oil refinery plants.

Hydrogen is the lightest and most volatile gas. Numerous studies (Machinery *et. al*. 2023) prove the release of biogenic hydrogen by algae, rather than its absorption. In our experiments, hydrogen diffused through a balloon. Studies on CO_2 absorption by the freshwater alga Chlorella vulgaris were conducted one month later using blow-off gases from the same technological installation, so the composition of the gas was different from the study period of marine microalgae (Table 2). The microalgae Chlorella vulgaris demonstrated significant absorption of C_1–C_5 methane series hydrocarbons. The microalgae Chlorella vulgaris demonstrated the ability to absorb CO_2 with an efficiency of 88.48%. After 1 day, a significant increase in the percentage of nitrogen and oxygen was observed, from a total of 16.50 to 92.74 wt.% by gas volume. Studies on changes in the genome, abundance, and other biological characteristics of the microalgae were not conducted due to the short duration of the experiment (24 h). Since microalgae cannot go through growth stages in such a short period of time, and the measured components show only slight changes, the composition of the aqueous medium in the initial and post-experimental conditions of the study with Chlorella vulgaris is presented for reference (Table 3). Studies conducted on CO_2 absorption for actual gases in the industrial production of isoprene did not correlate with the efficiency of the absorption capacity of all microalgae strains used when the gas components changed due to compositional differences. However, the data obtained provide general information on the feasibility of the CO_2 absorption method in the presence of C_1–C_5 methane series hydrocarbons. Therefore, it is possible to increase the efficiency of CO_2 and C_1–C_5 absorption by selecting the wavelength

Table 2: Changes in the composition of the blow-off gas after repeated passes through the photobioreactor

Components	Initial	After 3 runs	After 5 runs	After 7 runs	After 24 h
	wt.%				
H_2	42.59	49.84	43.93	44.91	2.74
O_2	6.89	4.80	4.40	5.49	9.61
N_2	9.61	12.58	18.04	23.01	83.13
CO	2.35	3.58	2.71	2.57	0
CO_2	7.64	3.88	4.26	2.97	0.88
CH_4	13.89	16.43	18.31	16.63	0
Ethane	4.29	2.23	2.29	1.79	1.92
Derivatives of propane	8.02	4.38	4.03	1.95	0.85
Derivatives of butane	4.04	1.99	1.78	0.58	0.11
Derivatives of pentane	0.64	0.29	0.26	0.09	0

Table 3: Changes in the composition of the aqueous (nutrient) medium with Chlorella vulgaris

Defined indicator	Initial media	After blow-off gases (after 24 h)	After smoke gases (after 24 h)
Potential of hydrogen (pH)	4.95	5.81	5.32
Nitrite ion: NO_2^- millgram per gram (mg/L)	11.86	9.32	11.35
Nitrate ion: NO_3^- (mg/L)	1095.60	1224.9	1156.85
Ammonium ion: NH_4^+ (mg/L)	8.51	77.22	14.14
Phosphate ion PO_4^{3-} (mg/L)	98.0	101.0	97.0

of illumination, the temperature of the microalgae suspension, the bubbling rate, and the size of the gas bubbles.

CONCLUSIONS

Absorption of gases discharged from isoprene production by microalgae was studied for the first time. During isoprene synthesis by two-stage dehydrogenation of isopentane, waste gases such as light hydrocarbons C_1–C_5 and inert gases CO, CO_2, and N_2 were formed. Since the gas mixture was not utilized, the gases were sent to the furnace for combustion according to the technological scheme. Then, the combustion products of the waste gas and furnace gas were released into the atmosphere. Expert assessments on the calculation of CO_2 emissions from isoprene production are not presented in the literature. According to estimates, the carbon dioxide emissions are equivalent to 10,000 to 15,000 tons per year. Microalgae cultivation technology is recognized as the most effective and natural technology for utilizing carbon dioxide emissions to harness greenhouse gases. In this research, Isochrysis galbana, Tetraselmis suecica, and Chlorella vulgaris were selected to study the absorption capacity of CO_2 and hydrocarbon gases in the isoprene production discharged gases. Studies have shown that Chlorella vulgaris absorbs CO_2 and methane most effectively, reducing carbon dioxide content from 7.64 to 0.82 wt.% and methane content from 13.89 to 0 wt.%. All microalgae completely utilize carbon monoxide. C1–C5 hydrocarbon gases are absorbed most effectively by mixed strains of Tetraselmis suecica and Isochrysis galbana. Comparative studies on biological fixation of discharged gases indicate that the marine microalgae strains Tetraselmis suecica and Isochrysis galbana and their mixtures, as well as the freshwater microalgae strain Chlorella vulgaris, have the potential to serve as reliable and stable CO_2 biofixation mechanisms in the purification of discharged gases. The development of disposal technologies for discharged gases can eliminate the need for a combustion stage, reduce CO_2 and combustion heat emissions by a factor of 10, reduce anthropogenic impacts on the environment, and slow down the pace of global warming.

AUTHOR CONTRIBUTIONS

F.B. Shevlyakov corresponding author, performed the main experiments, participated in the analysis of chromatography data, interpretation of the results, and preparation of the manuscript. O.R. Latypov organized, financed, and edited the work. A.B. Laptev prepared an experimental plan, translated and corrected the text of the article, and D.R. Latypova conducted laboratory studies.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
^oC	Degree Celsius
µl	microliter
$C_1–C_5$	methane – pentane
$C_2–C_5$	Ethane – pentane
CH_4	Methane
cm^3	Cubic centimetre
cm^3/min	Cubic centimeter per minute
CO	Carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
HCO_3^-	Hydro carbonate ion
h	Hour
g/L	Grams per liter
kg	Kilogram
$kg\ CO_2/1\ kg$	Kilogram carbon dioxide per kilogram microalgae
micromole photons/(m^2s)	Micromole of photons per square meter per second
mg/L	Milligrams per liter
mL	Milliliter
mL/min	Milliliter per minute
mm	Millimeter
m^2/s	Square meter per second
N_2	Nitrogen
NO_2^-	Nitrite ion
NO_3^-	Nitrate ion
NH_4^+	Ammonium ion
O_2	Oxygen
pH	Potential of hydrogen
PO_4^{3-}	Phosphate ion
ppm	Part per million
t/ha/y	Tons per hectare per year
wt.%	Weight percent

REFERENCES

Ahmed, R.; Liu, G.; Yousaf, B.; Abbas, Q.; Ullah, H.; Ali, M.U., (2019). Recent advances in carbon-based renewable adsorbent for selective carbon dioxide capture and separation-A review. J. Cleaner Prod., 118409 **(20 pages)**.

Arenas, E.G.; Rodriguez Palacio, M.C.; Juantorena, A.U.; Fernando, S.E.L.; Sebastian, P.J., (2016). Microalgae as a potential source for biodiesel production: techniques, methods, and other challenges. Int. J. Energy Res., 41(6): 761–789. **(29 pages).**

Arredondo Trapero F.G.; Guerra Leal E.M.; Kim, J., (2023). Effectiveness of the voluntary disclosure of corporate information and its commitment to climate change. Global J. Environ. Sci. Manage., 9(4): 1033-1048 **(15 pages).**

Austin, B.; Day, J.G., (1990). Inhibition of prawn pathogenic Vibrio spp. by a commercial spray-dried preparation of Tetraselmis suecica. Aquaculture. 90(3): 389-392 **(4 pages).**

Austin, B.; Baudet, E.; Stobie M., (1992). Inhibition of bacterial fish pathogens by tetraselmis suecica. J. Fish Dis., 15(1): 55-61 **(7 pages).**

Aryal, N.; Ottosen, L.D.M.; Kofoed, M.V.W.; Pant, D., (2021). Emerging technologies and biological Systems for biogas upgrading: 1st edition - Elsevier Inc.: 387-388 **(2 pages).**

Bajguz, A.; Hayat, S., (2009). Effects of brassinosteroids on plant responses to environmental stresses. Plant Physiol. Biochem., 47(1): 1–8 **(8 pages).**

Balagurumurthy, B.; Oza, T.S.; Bhaskar, T. Adhikari, D.K., (2013) Renewable hydrocarbons through biomass hydropyrolysis process: challenges and opportunities. J Mater Cycles Waste Manage., 15: 9–15 **(6 pages).**

Bhatti, S.; Huertas, E.; Colman, B., (2002). Acquisition of inorganic carbon by the marine haptophyte Isochrysis galbana (Prymnesiophyceae). Plant Physiol. Biochem., 38: 914–921 **(8 pages).**

Carballo-Cárdenas, E.C.; Tuan, P.M.; Janssen, M. and Wijffels R.H., (2003). Vitamin E (α-tocopherol) production by the marine microalgae Dunaliella tertiolecta and Tetraselmis suecica in batch cultivation. Biomol. Eng., 20: 139–147 **(9 pages).**

Cheah, W.Y.; Show, P.L.; Chang, J.S.; Ling, T.C.; Juan, J.C., (2015). Biosequestration of atmospheric CO_2 and flue gas-containing CO_2 by microalgae. Bioresour. Technol., 184: 190–201 **(12 pages).**

Cheah, W.Y.; Show, P.L.; Chang, J.S.; Ling, T.C.; Juan, J.C., (2015). Biosequestration of atmospheric CO_2 and flue gas-containing CO_2 by microalgae. Bioresour. Technol., 184: 190–201 **(12 pages).**

Chen, C.Y.; Kao, P.C.; Tsai, C.J.; Lee, D.J.; Chang, J.S., (2013). Engineering strategies for simultaneous enhancement of C-phycocyanin production and CO_2 fixation with spirulina platensis. Bioresour. Technol., 145: 307–312 **(6 pages).**

Cho, J.M.; Oh, Y.-K.; Park, W.-K.; Chang, Y.K., (2020). Effects of nitrogen supplementation status on CO_2 biofixation and biofuel production of the promising microalga chlorella sp. ABC-001. J. Microbiol. Biotechnol., 30(8): 1235–1243 **(9 pages).**

Coutinho, P.; Rema, P.; Otero, A.; Pereira, O.; Fábregas, J., (2006). Use of biomass of the marine microalga Isochrysis galbana in the nutrition of goldfish (carassius auratus) larvae as source of protein and vitamins. Aquacult. Res., 37(8): 793–798 **(6 pages).**

Culaba, A.B.; Ubando, A.T.; Ching, P.M.L.; Chen, W.-H.; Chang, J.-S., (2020). Biofuel from microalgae: sustainable pathways. Sustainability. 12(19): 8009 **(19 pages).**

Deamici, K.M.; Santos, L.O.; Costa, J.A.V., (2019). Use of static magnetic fields to increase CO_2 biofixation by the microalga chlorella fusca. Bioresour. Technol., 276: 103–109 **(7 pages).**

De Morais, M.G.; Costa, J.A.V., (2007). Isolation and selection of microalgae from coal fired thermoelectric power plant for biofixation of carbon dioxide. Energy Convers. Manage., 48(7): 2169–2173 **(5 pages).**

Dissanayake, P.D.; You, S.; Igalavithana, A.D.; Xia, Y.; Bhatnagar, A.; Gupta, S.; Ok, Y.S., (2019). Biochar-based adsorbents for carbon dioxide capture: A critical review. Renewable Sustainable Energy Rev., 109582 **(53 pages)**.

Duarte, J.H.; Fanka, L. and Costa, J.A.V., (2016). Utilization of simulated flue gas containing CO_2, SO_2, NO and ash for Chlorella fusca cultivation. Bioresour. Technol., 214: 159–165 **(7 pages).**

Farajzadeh Z.; Nematollahi M.A., (2023). Components and predictability of pollutants emission intensity. Global J. Environ. Sci. Manage., 9(2): 241-260 **(19 pages).**

Gong, J. and You, F., (2014). Value-Added Chemicals from Microalgae: Greener, More Economical, or Both? ACS Sustainable Chem. Eng., 3(1): 82–96 **(15 pages).**

Guillard, R.R., (1975) Culture of phytoplankton for feeding marine invertebrates. In: Smith, W.L.; Chanley, M.H. (Eds.) Culture of marine invertebrate animals. Plenum, New York. **(31 pages).**

Hussain, M.; Liu, G.; Yousaf, B.; Ahmed, R.; Uzma, F.; Ali, M.U.; Ullah, H. and Butt A.R., (2018). Regional and sectoral assessment on climate-change in Pakistan: Social norms and indigenous perceptions on climate-change adaptation and mitigation in relation to global context. J. Cleaner Product., 200: 791–808 **(18 pages)**.

Irianto, A.; Austin, B., (2002). Probiotics in aquaculture. J. Fish Dis., 25(11): 633-642 **(10 pages).**

Kamyab, H.; Chelliapan, S.; Kumar, A.; Rezania, S.; Talaiekhozani, A.; Khademi, T.; Rupani, P.F.; Sharma, S. (2019) Microalgal biotechnology application towards environmental sustainability Application of microalgae in wastewater treatment. 445–465 **(21 pages).**

Laptev, A.B.; Akhiyarov, R.J.; Lapteva, A.A.; Puzanov, A.I.; Zagorskikh, O.A. (2022).: Conference Series: J. Phys., 2373: 022008 **(11 pages).**

Li, S.; Chang, H.; Zhang, S. and Ho, S-H., (2023). Production of sustainable biofuels from microalgae with CO_2 bio-sequestration and life cycle assessment. Environ. Res., 227: 115730 **(24 pages)**.

Machineni. L.; Deepanraj, B.; Chew, K.W.; Rao, A.G. (2023). Biohydrogen production from lignocellulosic feedstock: Abiotic and biotic methods. Renewable Sustainable Energy Rev., 182: 113344 **(14 pages).**

Masojídek, J. and Torzillo, G., (2014). Mass cultivation of freshwater microalgae. Reference module in earth systems and environmental sciences. Elsevier Inc., 2226�2235 **(10 pages)**.

Mitsubishi Heavy Ind Ltd., (1991) Patent JPH03154616 (A). B01D53/34; B01D53/62; B01F1/00; C01B32/50; C10L5/44. Recovery and fixation of carbon dioxide **(2 pages)**.

Muller-Feuga, A., (2004). Microalgae for aquaculture: The current global situation and future trends. In: Richmond A, editor. (2004). Handbook of Microalgal Culture. Biotechnology and Applied Phycology. Oxford: Blackwell Science Ltd. **(4 pages)**.

Otsuka, H., (1961). Changes of lipid and carbohydrate contents in chlorella cells during the sulfur starvation, as studied by the technique of synchronous culture. J. General Appl. Microbiol., 7(1): 72–77 **(6 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Slegers, P.M.; Olivieri, G.; Breitmayer, E.; Sijtsma, L.; Eppink, M.H.M.; Wijffels, R.H. and Reith, J.H., (2020). Design of Value Chains for Microalgal Biorefinery at Industrial Scale: Process Integration and Techno-Economic Analysis. Front. Bioeng. Biotechnol., 8 **(24 pages)**.

Tredici, M.R.; Biondi, N.; Ponis, E.; Rodolfi, L. and Chini Zittelli, G., (2009). Advances in microalgal culture for aquaculture feed and other uses. New technologies in aquaculture: Improving production efficiency, quality and environmental management. Cambridge: Woodhead Publishing Ltd. **(1 page).**

Van Den Hende, S.; Han, V.; Boon, N., (2012). Flue gas compounds and microalgae: (Bio-) chemical interactions leading to biotechnological opportunities. Biotechnol. Adv., 30(6): 1405-1424 **(20 pages).**

Yilong, C.; Shuchuan, H.; Yanfeng Z., (2015). Method and device for providing plants and/or algae with heat and carbon dioxide with application of power plant flue gases. Patent RU2013147479 (A). A01G9/24; C01B32/50 **(13 pages)**.

Zeng, X.; Danquah, M.K.; Zhang, S.; Zhang, X.; Wu, M.; Chen, X.D.; Ng, I-S.; Jing, K. and Lu, Y., (2012). Autotrophic cultivation of Spirulina platensis for CO_2 fixation and phycocyanin production. Chem. Eng. J., 183: 192–197 **(6 pages).**

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ORIGINAL RESEARCH ARTICLE

Balancing environmental impact: A sustainability index analysis of sorghum production for food and feed

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sorghum is a grain-producing commodity with the seeds being a food source, while the leaves, stems, and bran serve as animal feed. The productivity depends on the specific variety, environment, infrastructure, and technology used. Sorghum cultivation in Indonesia is carried out primarily using agroforestry or monoculture. Despite not being as popular compared to rice and corn due to the prevalence of these staples in Indonesian diets, sorghum has the potential to replace corn because its cultivation is easier and the results are more profitable. Therefore, this study aimed to determine sustainability index and potential of sorghum for food and feed by identifying dimensions and attributes that influence sustainability.

METHODS: This study was conducted at Raji, Demak, Central Java, Indonesia in October 2023. Data were collected through focus group discussions and structural questionnaires consisting of 28 attributes associated with environmental, social, economic, and technological dimensions. Multidimensional scaling method and Rapfish software were used for data analysis. Monte Carlo analysis was used to ascertain sustainability level and attributes leverage, as well as check errors and variations in assessment.

FINDINGS: The results showed that sustainability index of sorghum for food and feed was 79.67, categorized as very sustainable. Analysis across four dimensions showed that the social dimension had the highest (83.80) sustainability index, followed by the technological (82.28), economical (77.46), and environmental (75.15) dimensions. A total of 12 attributes were found to greatly affect sustainability. These included land availability, the efficiency of water used, the prevention of natural resource exploitation, motivation level, minimal interference with primary agricultural activities, community acceptance, productivity, sales profit level, ease of sale and cultivation, tools availability, and technological sensitivity.

CONCLUSION: Sustainability index of sorghum for food and feed was categorized as very sustainable with a value of 79.67. This index consisted of the environmental (75.15), social (83.80), economical (77.46), and technological dimensions (82.28). The average productivity at the study site was 6-7 tons per hectare (tons/ha), with a production potency of 300-350 tons/year. Additionally, the potency of sorghum stover production was 471.8 ton per year of dry matter and could be used as feed for 163 animal units/year.

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INTRODUCTION

Sorghum is a versatile cereal grain plant used for multiple purposes including a source of food, feed, fuel, as well as industrial raw material. The various forms consist of grain, sweet sorghum, forage, and broom (Hao *et al.,* 2021). This plant holds a vital position as the most essential food crop in the world comparable to wheat, rice, maize, and barley (Rao *et al.*, 2014). The calorie content is approximately 332 calories per 100 grams (cal/g), with 11 percent (%) protein, 3.3% fat, 73% carbohydrates, and 28% calcium (Sihono *et al.,* 2019). Sorghum can be cultivated on suboptimal land with drought stress, high temperatures, less fertile soil, and minimal costs, and inputs (Dorcas *et al*., 2019). The planted area in Indonesia is estimated at 3,879 hectares (ha) with the largest occurring in East Nusa Tenggara (60%), while East Java, Central Java, West Java, Southeast Sulawesi, and West Nusa Tenggara account for 3-10%. Sorghum cultivation is carried out using agroforestry or monoculture but is not as popular compared to rice and corn, which are widely used as staples in Indonesian diets. However, sorghum has the potential to replace corn because the cultivation is easier and the results are more profitable. The productivity of several varieties in Gunung Kidul Indonesia with average 6.27 tons per hectare (tons/ha) is as follows: Bioguma (7.70), Plonco (8.41), Samurai (5.38), Kawali (8.21), Red Glutinous Sorghum (Ketan Merah**)** (3.91), and Black Sorghum Wareng (4.00) (Muazam *et al.,* 2023). The average productivity value is greater than the national average production of corn 5.71 tons/ha in Indonesia (BPS, 2021). The development in Indonesia has been very slow because farmers prefer to plant rice and corn. However, sorghum is more drought-resistant than corn, resulting in the development being directed at dry areas. The primary producers include the USA, Nigeria, Sudan, Mexico, and Ethiopia (USDA, 2022). Sorghum is a drought-tolerant plant and easier to cultivate depending on the variety, seed preparation, planting time, land preparation, planting, fertilizing, maintenance, and pest/disease control. The plant can grow optimally at 0-500 meters (m) above sea level using a monoculture or intercropping approach with secondary crops or vegetation on land. In this context, planting distance is calculated based on production purposes, either for food or feed. Sorghum needs water for optimal growth, specifically after seedling establishment, and is relatively more resistant to pests and diseases compared to other secondary crops. The common pests include sorghum fly (*Atherigona varia Soccata* (Rond.), *Prodenia litura* F., and *Spodoptera frugiperda* J.E. Smith (s). Furthermore, sorghum plays a significant role in global food security, offering an alternative feed option due to its ability to grow in arid and semi-arid areas. Environmental factors such as climate, soil, water, agricultural technology, and environmental changes can impact productivity for stable and sustainable food in the future. celsiusA temperature of more than 35 degrees Celsius (°C) can affect growth and crop yield (Chadalavada *et al*., 2021). Excessive humidity or prolonged rainy seasons also have the potential to reduce productivity (Hatfield *et al.,* 2011). Drought is a significant limiting factor in reducing crop yields, while other factors that affect productivity include soil type and fertility. Sandy, or clayey soils, and a potential of hydrogen (pH) close to neutral, support the growth of sorghum (Abreha *et al*., 2022). Moreover, fertilizer plays a key role in increasing productivity, providing major nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Samijan *et al.*, 2023; Samimi *et al.,* 2023). In this context, it is essential to adjust the nitrogen fertilizer dose based on soil conditions and local environmental factors. Land without N fertilizer resulted in a decrease in sorghum yield to 39.3% (Ganyo *et al.,* 2019). The optimum fertilizer dose per hectare is nitrogen (N) 160.4 kilograms (kg), diphosphorus penta oxide (P_2O_5) 43.7 kg, and dipotassium oxide (K_2O) 124.9 kg (Karimuna *et al.,* 2020). According to a previous study, understanding specific agricultural sites, including soil type and climatic conditions, is crucial for effective fertilization (Akinseye *et al.,* 2020). To significantly increase productivity, there is also a need to use appropriate irrigation technology (Ghalkhani *et al.,* 2023). Water availability during the growth phase plays a very important role in determining crop yields (Darmawan *et al.,* 2023). Meanwhile, sorghum is very sensitive to waterlogging at the stage of the fifth leaf and flowering. High humidity can increase the risk of pests and diseases, showing the need for pest control strategies (Huang *et al.,* 2013). Sorghum has economic value as food, feed, energy, and industry. This is attributed to its potential ability to substitute rice and corn or process into diversified products (Pontieri and Giudice, 2016). In a circular and zero-waste economy, sorghum is a sustainable source of biomass (Babicka *et al.,* 2022), and by-products including stover, stems, and bran can be used as feed. The nutrient of stover based on the dry matter comprises 7.82% crude protein (CP), 2.60% extract ether (EE), 28.94% crude fiber (CF), 11.43% ash, and 40.57% nitrogen-free extract (NFE) (Korima *et al.,* 2022). At the flowering stage, the nutrient content includes 10.8% water, 6.70% ash, 8.79% CP, 1.20% EE, 27.88% CF, and 49.83% total digestible nutrient (TDN) (Sriagtula *et al.*, 2017). Sorghum stalks contain roomi used as a source of energy for feed, and the stover nutrient from several genotypes ranges from 7.91-9.30% CP, 1.91-2.69% EE, 33.41-37.57% CF, and 8.25-9.11% ash (Harmini *et al.,* 2022). Singh *et al.*, (2018) estimated the energy of sorghum stover for ruminants at 2.0 kcal/g, while the potency for production is approximately 20-40 tons/ha depending on the level of soil fertility and variety. Meanwhile, sorghum bran contains a high protein level and is also a source of kafirin, xyloglucan, and glucan used as industrial raw materials (Sihono *et al.,* 2019). Agricultural sustainability is usually measured based on certain dimensions (Sulewski *et al.,* 2018), including social, economic, and environmental (Assan, 2023). Achieving sustainability, specifically in terms of food security, requires a comprehensive assessment of the interplay between different agro-economic and socio-environmental indicators (Karandish *et al.,* 2022). Therefore, this study aimed to assess sustainability index and potential of sorghum for food and feed. The results provide information on sustainability index from environmental, social, economic, and technological dimensions.

MATERIALS AND METHODS

Data retrieval

This study was carried out at Raji, Demak, Central Java, Indonesia in 2023, and data were collected through focus group discussions (FGD). A survey was conducted on eight experts in sorghum crop and business actors who have at least experience five years, using structural questionnaires. FGD assessed the current business environment supporting production as basic information for designing sustainability dimensions and attributes. Sustainability dimensions used were environmental, social, economic, and technological. The indicators included 28 attributes in a structural questionnaire with answer choices. Sustainability index (score) of each dimension was determined by entering the scores of each attribute into Multidimensional scaling (MDS) software. The scores were obtained from the respondents, namely 1 (too bad), 2 (bad), 3 (medium), 4 (fairly good), and 5 (good).

Data analysis

MDS through the Rap method (Rapid Appraisal for grain sorghum plants) was used for data analysis. This was developed and adopted from the Raffish (Rapid Appraisal for Fish) method to determine sorghum production sustainability using the following steps (Lloyd *et al.,* 2022):

1) Appraise dimensions and attributes of sustainability. This study used four dimensions with 28 attributes.

2) Assess attributes using scores. The scores of attributes formed a matrix X (n x p), where n is the regions and reference points number, and p is attributes used number. Each score was standardized using Eq. 1 (Borg *et al.,* 2018).

$$X_{ik}sd = \frac{X_{ik} - X_k}{S_k} \quad (1)$$

$X_{ik}sd$ = i-th regional standard score (including reference points) = 1, 2, …, n for each attribute = 1, 2, …, p

X_{ik} = i-th standard score (including reference points) = 1, 2, ..., n for each attribute = 1, 2, ..., p

X_k = average score on each attribute = 1, 2, …, p

S_k = scores standard deviation for each attribute = 1, 2, …, p

The shortest distance from the Euclidian distance was calculated with Eq. 2 (Borg *et al.*, 2018), and then using the regression Eq. 3 (Borg *et al.*, 2018), it was projected into two-dimensional Euclidian space (d12). The regression process used the ALSCAL algorithm by carrying out iterations leading to an intercept value of zero (a = 0). This change led to Eq. 4 (Borg *et al.,* 2018), and the repetition process was stopped after the stress (S) value was <0.25. The S value was obtained using Eq. 5 as follows (Borg *et al.,* 2018):

$$d = \sqrt{\left(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \dots\right)} \quad (2)$$

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (3)$$

$$d_{12} = bD_{12} + e; \quad (4)$$

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (5)$$

Sustainability indices and status were categorized as follows: not sustainable (0.00−25.00), less sustainable (25.01−50.00), moderately sustainable (50.01−75.00), and highly sustainable (75.01−100.00), according to (Rachman *et al.,* 2022).

Analysis of sensitivity (leverage) was conducted to determine attributes that greatly influence sustainability. This analysis was based on the sequence of changes in root mean square (RMS) ordination on the x-axis. When RMS had a significant value, it means that the role of attributes was prominent in sustainability status. Monte Carlo analysis to estimate the error rate in MDS model for all dimensions used a 95% confidence level. The smaller the difference between MDS and Monte Carlo analysis results, the better the resulting model. Furthermore, the goodness of fit was designated in the S value and coefficient of determination (R^2). The low S value means a good match and The high S value shows the opposite. The S value of less than 0.25 showed a good model, while an R^2 value close to 1 denoted that attributes used were quite accurate (Borg *et al.*, 2018; Samimi and Moghadam, 2024).

RESULTS AND DISCUSSION

Dimensions and attributes

FGD produced four dimensions including environmental, social, economic, and technological with several attributes (Table 1). Attributes in each dimension were used as material to obtain sustainability index. The results showed that sorghum as food and feed had sustainability index of 79.67, with a stress value of 0.1379 (Table 2). This shows the validity and accuracy of the four dimensions determined by Monte Carlo test.

Environmental dimension

Environmental dimension sustainability index was recorded at 75.15, showing the dimension had a significant impact on sorghum cultivation. The three crucial attributes from this dimension were land availability, water use efficiency, and the prevention of natural resource exploitation (Table 1). At the study site, sorghum was planted in rotation with shallot plants, commencing in March during the transition from the rainy to the dry season. The available land was relatively large, reaching 100 ha and sorghum plant was best suited to the characteristics and the season, resulting in optimal production. The

Table 1. Attributes of four dimensions for sustainability of sorghum as food and feed

Environmental	Social	Economic	Technological
1. Land availability for sorghum cultivation	1. Farmer education level	1. Productivity of sorghum plant	1. Ease of sorghum cultivation
2. Water use efficiency for sorghum cultivation	2. Family workforce involvement	2. Management of sorghum plant	2. Tools availability for sorghum cultivation
3. Level of pest and disease control	3. Motivation level of sorghum cultivation	3. Increasing business scale	3. Potential to increase sorghum production
4. Efficient use of fertilizer for sorghum cultivation	4. Level of community acceptance of sorghum cultivation	4. Increasing worker welfare	4. Level of technological sensitivity
5. Level of water, land, and air pollution	5. Sorghum cultivation does not affect the main work	5. Efficient use of production facilities	5. Ease of pest and disease control
6. The prevention of natural resource exploitation in sorghum cultivation	6. Worker knowledge level	6. Ease of obtaining production facilities	6. Ease level of processing results
	7. Work safety level	7. Ease of selling sorghum	
	8. Suitability of business type	8. Profit level of sorghum sales	

Table 2. Sustainability index and status of sorghum as food and feed

Dimension	Index	Stress	R^2(SQR)	Status
Environmental	75.15	0.1434	0.9319	highly sustainable
Social	83.80	0.1335	0.9457	highly sustainable
Economical	77.46	0.1341	0.9430	highly sustainable
Technological	82.28	0.1407	0.9269	highly sustainable
Average	79.67	0.1379	0.9368	highly sustainable

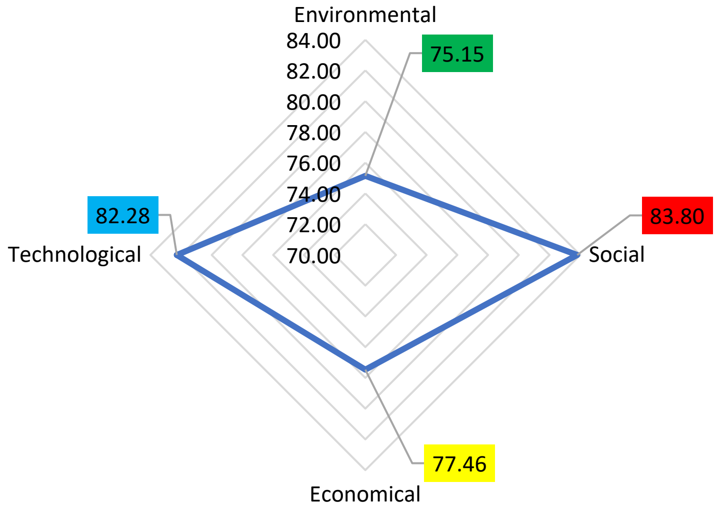

Fig. 1: Sustainability level sorghum as a source of food and feed

availability of land for cultivation significantly impacts food security and a sustainable environment, underscoring the importance of maximizing productivity (Fig. 2). Sustainable agricultural methods such as agroforestry and crop-livestock integration are effective in increasing land use efficiency by optimizing the use of available natural resources (Zomer *et al.*, 2014. Furthermore, soil quality and field characteristics can help maximize sorghum yields with minimal land exploitation (Foley *et al.*, 2011). Water use at the study site was very efficient, with the sources being irrigation and rainwater. Irrigation practice is one way to increase water use efficiency in sorghum cultivation, including the use of technology such as drip or sensor-based irrigation that accurately measures soil moisture to determine when plants need water. Using these methods, farmers can avoid wasting water and provide an accurate amount based on plant needs. Furthermore, sorghum is tolerant to drought (Abreha *et al.*, 2022), and has a greater ability to maintain water compared to maize as stated by Safian *et al.* (2022). The optimal water use requirement at an early stage was 78.71 mm, then 173.20 mm, and 174.46 mm in mid-season. This means that the total water requirement in all stages of growth and development was 401.25 mm (Shenkut *et al.*, 2013). Sorghum has a 20% greater water use efficiency in arid areas compared to maize, resulting in good prospects for wide-scale cultivation and climate variations (Hossain *et al.*, 2022). Based on the result, the natural resource prevention exploitation at the study site was relatively high. Cultivation was carried out using a rotation approach with shallot to avoid exploitation in line with the principles of sustainable agriculture. Rotating sorghum with other crops such as legumes or cover crops can also increase soil fertility and reduce the land degradation risk (Aristya and Samijan, 2022). Conservation efforts, including the judicious use of fertilizers, contribute to maintaining soil fertility and reducing natural resource exploitation (Jug *et al.*, 2021). Furthermore, environmental impact analysis and sustainability indices between sorghum production and other crops may vary depending

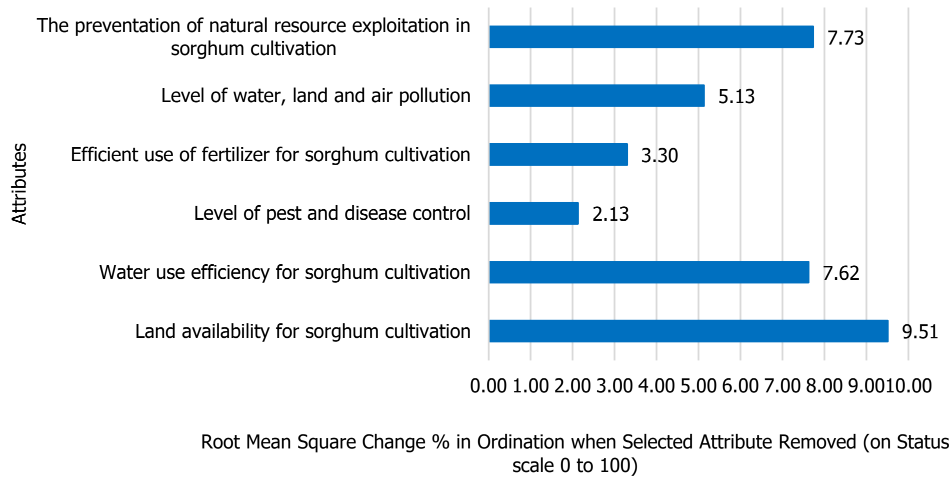

Fig. 2: Environmental attributes leverage

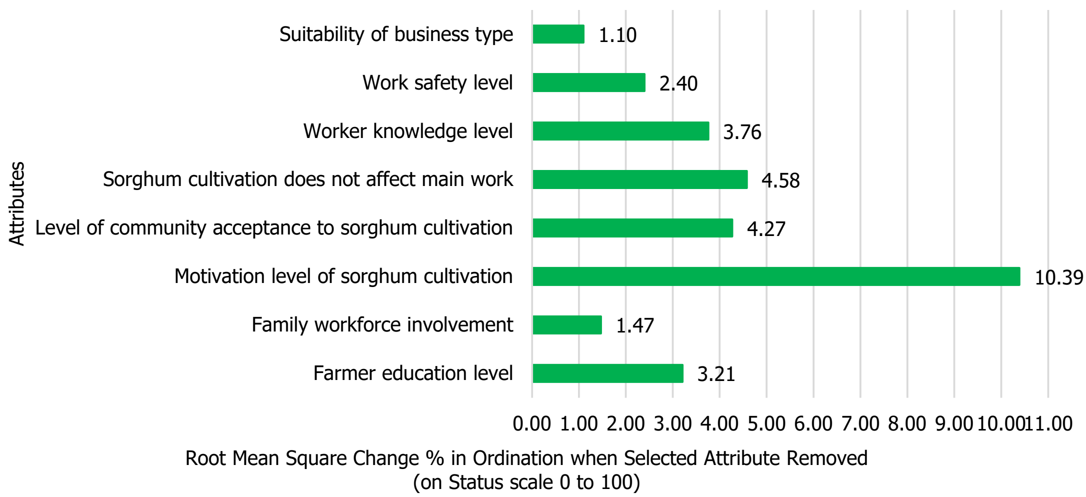

Fig. 3: Social attributes leverage

on various factors, including agricultural practices, local climate, and soil management. Some common considerations consist of water and pesticide use, greenhouse gas emissions, soil sustainability, as well as fertilizer requirements. In terms of water use, sorghum is often considered drought-resistant compared to several other food crops (Jamil *et.al.*, 2021; Behera, *et.al.*, 2022). This makes the plant suitable for areas experiencing drought or have limited water availability. Regarding fertilizer and pesticide use, sorghum may require less nitrogen fertilizer compared to crops such as corn (Pan and An, 2020). The plant can also efficiently remove heavy metals from contaminated soil (Zhuang *et.al.*, 2009). In terms of potential greenhouse gas emissions, several studies stated that sorghum had a lower carbon footprint compared to other food crops, such as corn. The use of biosolids as a nitrogen source in sweet sorghum production can reduce greenhouse gas emissions without losing yield (Glab and Sowinski, 2019). Concerning soil sustainability, cultivating this crop has previously been shown to improve soil chemical properties, such as increasing phosphorus content and available organic matter (Thawaro *et.al.*, 2017). Additionally, sorghum has the ability to emit allelochemicals with biological nitrification inhibition capacity, which can reduce nitrification and reduce nitrogen pollution (Ping et.al., 2009). This represents a positive factor in terms of soil sustainability. In the context of production for food and feed, differences may occur in terms of nutritional requirements and resource use. Production for animal feed may have higher sustainability in terms of resource efficiency because sorghum can grow well in areas that are less fertile or have low water availability (Sanni *et.al.*, 2022).

Social dimension

Social dimension sustainability index was recorded at 83.80, showing that the dimension had a significant impact on sorghum cultivation sustainability at the study site. The three crucial attributes from this dimension were the motivation level, minimal interference with primary agricultural activities, and the level of community acceptance (Table 1). Motivation, defined as the inner drive compelling an individual to take action, plays an important role in achieving desired purposes. In the context of sorghum cultivation, farmers showed high motivation which stemmed from the desire to use the land during the waiting period for the next crop planting season. This was further supported by the characteristics of sorghum being easy to cultivate, having relatively high production, a promising selling price, and ease of selling. According to a previous study, commodities with economic value and technical feasibility contribute to increased motivation among farmers (Lakitan, 2014). It was also found that sorghum cultivation at the study site did not affect the main work of shallot farming. Every year, shallot cultivation was carried out in two planting seasons. Following the second planting season, farmers use land and time to cultivate sorghum. In other words, farmer activities at the study location each year entailed using seasons I-II for planting shallots, and III for sorghum. This rotational approach was carried out to break the cycle of pests and diseases. Planting season III was in the dry season, and suitable for drought-resistant plants. Furthermore, the community acceptance level of sorghum cultivation at the study site was very good (Fig. 3). This was marked by a longstanding practice spanning generations, over 30 years. Local communities have good reason to accept this commodity, resulting in high sustainability.

Economical dimension

A total of eight attributes significantly impacted the economic dimension sustainability of sorghum production. Based on leverage analysis (Fig. 4), three attributes with the most sensitive influence included plant productivity, profit level of sales, and ease of selling. The analysis results for economic dimension obtained sustainability index of 77.46 (Table 2). This value showed that sorghum production supported economic development at the study site due to ease of selling. The production was relatively high (6-7 tons/ha) compared to the varieties of Numbu (4.12 tons/ha), Kawali (3.92 tons/ha), Unpad 1 (3.86 tons/ha), Batari (3.26 tons/ha), Keller (3.04 tons/ha), and Taomitsu (3.44 tons/ha) (Karimuna *et al.,* 2020). The potency of production amounted to 300-350 tons/y with a land area of 50 ha, attracting brokers eager to purchase sorghum from farmers as harvest approached. This efficient process ensured that farmers did not encounter difficulties selling the harvest and incurred minimal costs for marketing. Consequently, net income was derived by substrating the selling price from cultivation and production costs, showcasing efficient management. This condition shows that farmers produce sorghum to meet market demand, as also stated by Sulewski *et al.* (2018). Based on the results, the profit level at the study site was relatively high. Profit is one of business purposes, contributing significantly to sustainability. Sorghum prices ranged from US$ 0.39-0.58/kg, resulting in farmers earning a gross income of US$ 2,516.67-3,755.00/ha. In comparison, the profits in Yogyakarta and Central Java were estimated at US$ 882,03 and 813.07, respectively (Widodo *et al.,* 2023). The nominal income of farmers depends on the amount of production and selling price, with a higher selling price per unit of production, leading to greater profits (Septiadi *et al.,* 2023). Furthermore, ease of selling sorghum was facilitated by the readiness of brokers, contributing to cultivation sustainability. It is crucial to develop sorghum in areas with a feed industry to ensure market stability and raw material availability. The plant could also be developed in areas consuming the product as local food. The level of market demand had a significant impact on ease of selling, underscoring the importance of expanding market coverage (Fig. 4). Selling sorghum

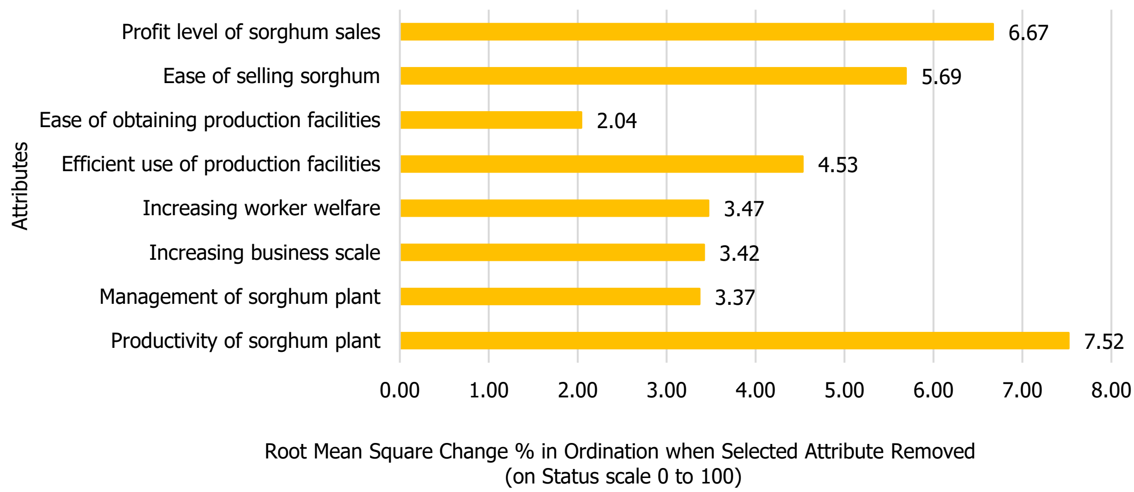

Fig. 4: Economical attributes leverage

in various markets serves multiple purposes, acting as a means of promoting new healthy food products, a potential marketing tool, and a trigger to promote upper-market segmentation, thereby increasing business capacity and marketing scope. According to a previous study, indicators of economic feasibility include ease of selling, reasonable price, low cost of input and production, as well as decent profits (Tugga *et al.,* 2023). The economic potential that could still be developed at the study site was using sorghum stover as feed. Despite the economic value, farmers have not yet explored this avenue due to a lack of knowledge and equipment for processing stover. The production of sorghum stover reached 9.44 tons/ha or 471.8 tons/y dry matter and could be used as feed for 163 animal units (AU)/year. This was lower compared to Cardoso *et al.* (2013) and Prakasham *et al.* (2015), which reported 15.62 tons/ha (harvested twice a year) and 24-32.5 tons/ha, respectively. To maximize the value of sorghum by-product, complete feed should be made from the main raw materials of stover and bran. The feed ration of steer with 66 and/or 100% sorghum silage supplementation increased body weight with economic benefits (Jabbari *et al.,* 2011).

Technological dimension

Technological dimension sustainability index was recorded at 82.28, greatly impacting sustainability of sorghum cultivation at the study site. The three crucial attributes from this dimension were ease level of cultivation, tools availability, and technological sensitivity (Table 1). Based on the results, ease level of sorghum cultivation adoption was very high, due to the knowledge and skills obtained directly from experienced farmers and passed down through generations. The technology of cultivation consists of various aspects including land processing, planting distance, planting methods, fertilization, pest and disease control, as well as the use of organic materials (Fig. 5). In essence, technology was adjusted to local requirements, aiming to increase production and maximize the benefits of sorghum as both food and feed. Indicators of the technical feasibility including ease of planting, maintenance, harvesting, post-harvest processes, and inputs (seeds, fertilizers, and pesticides) were easy and did not require high levels of equipment or skills. The availability of tools for cultivation and harvest is very important for sustainability of sorghum. Farmers used tools such as hoes, planter hole punchers, sickles, sprayers, and seed threshers. Despite being simple, these tools played crucial roles in land processing, planting, maintenance, pest and disease control, and harvesting. Furthermore, the sensitivity level of technology to the quality and quantity of sorghum production was relatively high. The potential for increased production was indicated through the adoption of superior varieties and balanced fertilization. In this context, farmers currently use local varieties and fertilizers were not applied in line with the recommended dose. Samurai

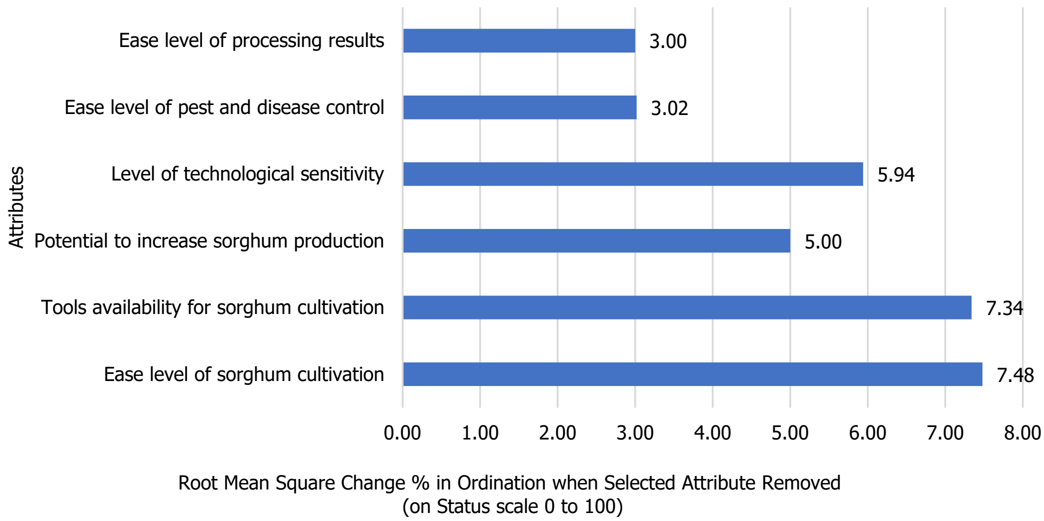

Fig. 5: Technological attributes leverage

variety showed more potency to be developed into forage, specifically in coastal areas, while the Numbu variety had more potency as a seed production. Farmers preferred local varieties due to the low height (2.1-2.5 m) and ease of harvest, short harvest time (90 days), and substantial production (6-7 tons/ha). According to a previous study, ecological type, variety, and planting distance suitability have a significant influence on sorghum yield (Yan *et al.,* 2023). The suitability of varieties with land conditions was identified as a crucial aspect of cultivation technology. Optimum yield in the dry land could be achieved with a recommended planting distance of 10 cm x 70 cm, 200 kg urea fertilizer, 100 kg SP-36, 50 kg/ha KCl, and 10 tons/ha organic fertilizer. The use of organic fertilizer for Numbu and Kawali varieties was found to increase the weight of stover and grain. In essence, both lowland and dryland could be developed into integrated agriculture through a community farming system approach, with the integration of ruminants supporting sustainable agriculture (Sekaran *et al.,* 2021).

CONCLUSION

In conclusion, farmers used local varieties and simple tools for cultivating and harvesting sorghum. Sustainability index obtained was 79.67, underscoring the highly sustainable character of the production across environmental, social, economic, and technological aspects. In terms of environmental sustainability (75.15), this study identified the crucial role of efficient land use, water management, and the prevention of resource exploitation. Social sustainability (83.80) was enhanced by factors such as farmer motivation, minimal interference with primary agricultural activities, and community acceptance. Economic sustainability (77.46) was evident through economic viability, high productivity, profitable sales, and easy market access. Furthermore, technological sustainability (82.28) was shown by the adaptability of sorghum to easy cultivation practices, the availability of necessary tools, and openness to technological advancements. In general, 12 attributes that greatly impacted sustainability included land availability, water use efficiency, the prevention of natural resources, motivation level of farmers, minimal interference with primary agricultural activities, community acceptance, productivity, sales profit level, ease of selling and cultivation, tools availability, as well as technological sensitivity. Based on the results, the average sorghum productivity ranged from 6-7 tons/ha, in addition to a production potency of 300-350 tons/y and a stover potency of 471.8 tons/y dry matter capable of feeding 163 animal units (AU) per year. This underscored the multifunctional and high-potential nature of sorghum in the region. This study not only affirmed the multifaceted role of the plant but also provided actionable insights for sustainable cultivation. Sustainability of sorghum as food and feed at the study site could be used as a reference for massive development. The results provided inspiration for other areas, specifically dry zones to develop sorghum with a good economic impact on the population. Optimal production at the study site remained uncertain, as farmers have not yet adhered to recommended fertilization practices. Furthermore, the application of simple tools and technology resulted in a high sustainability score. This study suggested that taking advantage of agricultural tools and technologies such as transplanters, drip irrigation, and harvesting machines might greatly improve sustainability index.

AUTHOR CONTRIBUTIONS

A. Prabowo performed study design, experimental design and methods, experimental activities, compiled and interpreted the data, data analysis, manuscript preparation and editing. R.N. Hayati performed experimental design and methods, experimental activities, data analysis, manuscript preparation and editing, literature review. D.D. Ludfiani performed experimental activities, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. S. Minarsih performed experimental design and methods, experimental activities, compiled and interpreted the data, manuscript preparation and editing, literature review. B. Haryanto performed experimental design and methods, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. A. Supriyo performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. S. Subiharta performed study design, experimental design and methods, experimental activities, manuscript preparation and editing, literature review. E. Nurwahyuni performed study design, experimental activities, data analysis, manuscript preparation and editing, literature review. Y. Hindarwati performed experimental activities, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. M.N. Setiapermas performed experimental design and methods, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. S. Sudarto performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. S. Samijan performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. B. Utomo performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. E. Winarni performed experimental activities, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. N.D. Suretno performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. W. Wibawa performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review. S. Agustini performed experimental design and methods, compiled and interpreted the data, data analysis, manuscript preparation and editing, literature review. A. Prasetyo performed study design, experimental design and methods, experimental activities, manuscript preparation and editing, literature review. F.R.P. Hantoro performed study design, experimental design and methods, experimental activities, manuscript preparation and editing, literature review. W. Hariyanto performed study design, experimental design and methods, experimental activities, manuscript preparation and editing, literature review. V.E. Aristya performed study design, experimental design and methods, compiled and interpreted the data, manuscript preparation and editing, literature review.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication or submission, and redundancy have been completely observed.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°C	Degree Celsius
ALSCAL	Alternating least-squares algorithm
AU	Animal Unit
cal	calorie
CF	Crude fiber
cm	centimeter
CP	Crude Protein
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
DM	Dry matter
EE	Extract eter
FGD	Focus Group Discussion
g	gram
ha	hectare
IDR	Indonesians Rupiah
K	Potassium
K_2O	Dipotassium oxide
Kcal	kilocalorie
KCl	Potassium chloride
kg	kilogram
m	meter
MDS	Multidimensional scaling
N	Nitrogen
NFE	Nitrogen-free extract
P	Phosphor
P_2O_5	Diphosphorus pentaoxide
pH	Potential of hydrogen
R^2	Coefficient of determination
Raffish	Rapid appraisal for fisheries, an analytical method to assess sustainability of fisheries based on a multidisciplinary method
SP-36	Single fertilizer with a P2O5 content of 36%
SQR	Structured query reporter, a programming language designed for generating reports from database management systems
Urea	Single fertilizer that has a high nitrogen (N) content of around 45 – 46%
TDN	Total digestible nutrient
USD	United States Dollar
USDA	United States Department of Agriculture

REFERENCES

Abreha, K.B.; Enyew, M.; Carlsson, A.S.; Vetukuri, R.R.; Feyissa, T.; Motlhaodi, T.; Geleta, M., (2022). Sorghum in dryland: sorghum's morphological, physiological, and molecular responses under drought stress. Planta. 255: 1-23 **(24 Pages).**

Akinseye, F.M.; Ajegbe, H.A.; Kamara, A.Y.; Adefisan, E.A.; Whitbread, A.M., (2020). Understanding the response of sorghum cultivars to nitrogen applications in semi-arid Nigeria using the agricultural production systems simulator. J. Plant Nutr., 43(6): 834-850 **(17 pages).**

Aristya, V.E.; Samijan, S., (2022). The yield gap of maize under intensive cropping system in Central Java. Planta Tropika. J. Agron. Sci., 10(1): 1-12 **(12 pages).**

Assan, N., (2023). Socio-cultural, economic, and environmental implications for innovation in sustainable food in Africa. Front. Sustainable Food Syst., 7: 1192422 **(18 pages)**.

Babicka, M.; Woźniak, M.; Bartkowiak, M.; Peplińska, B.; Waliszewska, H.; Zborowska, M.; Borysiak, S.; Ratajczak, I., (2022). Miscabanthus and sorghum as sustainable biomass sources for nanocellulose production. Ind. Crops Prod., 186: 115177 **(186 pages).**

Behera, P.P.; Saharia, N.; Borah, N.; Devi, S.H.; Sarma, R.N., (2022). Sorghum physiology and adaptation to abiotic stresses. Int. J. Environ. Clim. Change. 1005-1022 **(18 Pages)**.

Borg, I.; Patrick, J.F.; Groenen; Mair, P., (2018). Applied multidimensional scaling and unfolding. Springer Brief in Statistics **(122 pages).**

BPS-Statistics Indonesia, (2021). Analysis of maize and soybean productivity in Indonesia. **(134 pages).**

Cardoso, W.S.; Tardin, F.D.; Tavares, G.P.; Queiroz, P.V.; Mota, S.S.; Kasuya, M.C.M.; Queiroz, J.H., (2013). Use of sorghum straw (*Sorghum bicolor*) for second generation ethanol production: pretreatment and enzymatic hydrolysis. Quim. Nova., 36(5): 623-627 **(5 pages).**

Chadalavada, K.; Kumari, B.D.R.; Umar, T.S., (2021). Sorghum mitigates climate variability and changes in crop yield and quality. Planta. 253: 113 **(19 Pages).**

Darmawan, D.P.; Arisena, G.M.K.; Djelantik, A.A.A.W.S.; Krisnandika, A.A.K.; Dewi, N.L.M.I.M.; Korri, N.T.L.; Sukendar, N.M.C., (2023). Farmers' motivation and obstacles in the smallest available agricultural region. Global J. Environ. Sci. Manage., 9(4): 967-982 **(16 pages).**

Dorcas, K.; Koech, O.K; Kinama, J.M.; Chemining'wa, G.N.; Ojulong, H.F., (2019). Sorghum production practices in an integrated crop-livestock production system in Makueni County, Eastern Kenya. Trop. Subtropical Agroesyst., 22: 13-23 **(11 pages).**

Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; Balzer, C.; Bennett, E.M.; Carpenter, S.R.; Hill, J.; Monfreda, C.; Polasky, S.; Rockström, J.; Sheehan, J.; Siebert, S.; Tilman, D.; Zaks, D.P.M., (2011). Solutions for a cultivated planet. Nature. 478(7369): 337-342 **(6 pages).**

Ganyo, K.K.; Muller, B.; Ndiaye, M.; Gaglo, E.K.; Guissé, A.; Adam, M., (2019). defining fertilization strategies for sorghum (Sorghum bicolor (L.) Moench) production under sudano-sahelian conditions: Options for late basal fertilizer application. Agronomy. 9(11): 1-18 **(18 pages).**

Ghalkhani, A.; Golzardi, F.; Khazaei, A.; Mahrokh, A.; Illés, Á.; Bojtor, C.; Mousavi, S.M.N.; Széles, A., (2023). Irrigation management strategies to enhance forage yield, feed value, and water-use efficiency of Sorghum Cultivars. Plants. 12(11): 1-18 **(18 pages).**

Glab, L.; Sowinski, J., (2019). Sustainable production of sweet sorghum as a bioenergy crop using biosolids taking into account greenhouse gas emissions.. Sustainability. 11: 3033 **(17 pages)**.

Hao, H.; Li, Z.; Leng, C.; Lu C.; Luo H.; Liu Y.; Wu X.; Liu Z.; Shang L.; Jing H.C., (2021). Sorghum breeding in the genomic era: opportunities and challenges. Theor. Appl. Genet., 134**:** 1899–1924 **(36 pages).**

Harmini; Fanindi, A.; Sutedi, E.; Herdiawan, I.; Sajimin, (2022). Nutritional content, performance, and ratooning ability of four sorghum genotypes. The 2nd Intern. Conference Environ. Sustainable Anim. Ind., 2nd ICESAI 2021 **(5 pages).**

Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D., (2011). Climate impacts on agriculture: implications for crop production. Agron. J., 103(2): 351-370 **(20 pages).**

Hossain, S.; Islam, N.; Rahman, M.; Mostofa, M.G.; Khan, A.R., (2022). Sorghum: a prospective crop for climatic vulnerability, food, and nutritional security. J. Agric. Food Res., 8: 100300: 1-9 **(9 pages).**

Huang, Y.; Sharma, H. C.; Dhillon, M. K., (2013). Bridging conventional and molecular genetics of sorghum insect resistance. Plant Genet. Genom.: Crops Models. 11: 367-389 **(23 Pages).**

Jabbari, H.; Tabatabaei, S.N.; Kordnejad, E.; Modarresi, M.; Tabeidian, S.A., (2011). Effect of dietary corn silage replacement with sorghum silage on performance and feed cost of growing steers. Online J. Animal Feed Res., 1(1): 14-21 **(8 pages).**

Jamil, S.; Shahzad, R.; Ahmad, S.; Ali, Z.; Shaheen, S.; Shahzadee, H.; Fatima, N.; Sharif, I.; Aleem, M.; Sultana, R.; Fatima, R.; Rahman, S.U.; Iqbal, M.Z., (2021). Climate change and role of genetics and genomics in climate-resilient sorghum. Dev. Clim. Res. Crops. 111-138 **(28 pages).**

Jug, I.; Brozović, B.; Dević, B.D.; Wilczewski, E.; Vukadinović, V.; Stipešević, B.; Jug, D., (2021). Response of crops to conservation tillage and nitrogen fertilization under different agroecological conditions. Agronomy. 11(2156): 1-18 **(18 pages).**

Karandish, F.; Nouri, H.; Brugnach, M. (2021) Agro-economic and socio-environmental assessments of food and virtual water trades of Iran. Sci. Rep., 11: 15022 **(16 pages)**.

Karimuna, S.R.; Wahab, A.; Warda; Baharudin., (2020). The effectiveness of fertilizing to increase growth and productivity of sorghum on dry land and marginal in Southeast Sulawesi. IOP Conference. Environ. Sci., 484: 012073 **(9 pages).**

Korima, I.; Mansyur; Setiyatwan, H., (2022). Prospects of development of sorghum as ruminant forage feed in Indonesia. J. Trop. Anim. Nutri. Feed Sci., 4(3):109-112 **(4 pages).**

Lakitan, B., (2014). Inclusive and sustainable management of suboptimal lands for productive agriculture in Indonesia. J. Lahan Suboptimal. 3(2): 181–192 **(12 Page).**

Lloyd, C.; Ananthan, P.S.; Ramasubramanian, V.; Sugunan, V.V.; Panikkar, P.; Landge, A.T., (2022). Rapid reservoir fisheries appraisal (r-RAPFISH): Indicator-based framework for sustainable fish production in Indian reservoirs. J. Clean. Prod., 379: 134435. **(17 pages).**

Muazam, A.; Daryono, B. S.; Kristamtini., 2023. Production competitiveness of regional sorghum genotypes against new, enhanced varieties and their morphological traits in Gunung Kidul, Yogyakarta, Indonesia. Biodivers. 24(9): 4943-4948 **(6 pages)**.

Pan, L.; An, Dong., (2020). Nitrogen utilization is lower for sorghum-based diets compared with corn-based diets in pigs. Livest. Sci., 237: 104066 **(6 pages)**.

Pontieri, P.; Giudice, L.D., (2016). Sorghum: a novel and healthy food. In: caballero (eds) encyclopedia of food and health. Acad. Press. 33-42 **(10 pages).**

Prakasham, R.S.; Nagaiah, D.; Vinutha, K.S.; Uma, A.; Chiranjeevi, T.; Umakanth, A.V.; Rao, P.S.; Yan N., (2015). Sorghum biomass: a novel renewable carbon source for industrial bioproducts. Biofuels., 5(2): 159-174 **(16 pages).**

Rachman, B.; Ariningsih, E.; Sudaryanto, T.; Ariani, M.; Septanti, K.S.; Adawiyah, C.R.; Ashari; Agustian, A.; Saliem, H.P.; Tarigan, H.; Syahyuti; Yuniarti, E., (2022). Sustainability status, sensitive and key factors for increasing rice production: A case study in West Java, Indonesia. Plos One. 17(12): 1-19 **(19 pages).**

Rao, S.P.; Reddy, B.V.S.; Nagaraj, N.; Upadhyaya, H.D., (2014). Sorghum production for diversified uses. in: genetics, genomics, and breeding of sorghum. series on genetics, genomics, and breeding of crop plants. CRC Press (Taylor and France), Boca Raton, 01-27. ISBN 9781482210088 **(28 pages).**

Sanni, A.; Adegboyega, O.; Yahya, S. (2022). Sustainability study of sugarcane and sweet sorghum as feedstocks for biotehanol production. Sci. Open. Preprints. 2022 **(30 Pages).**

Safian, N.; Naderi, M.R.; Torabi, M.; Soleymani, A.; Salemi, H.R., (2022). Corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) yield and nutritional quality affected by drought stress. Biocat. and Agric. Biotechnol., 45(102486): 1-8 **(8 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Samimi, M.; Moghadam, H., (2024). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustain. Energy Rev., 190: 113969 **(10 pages).**

Samijan, S.; Minarsih, S.; Jauhari, S.; Basuki, S.; Susila, A.; Nurwahyuni, E.; Hindarwati, Y.; Supriyo, A.; Aristya, V.E., (2023). Revitalizing sub-optimal drylands: Exploring the role of biofertilizers. Open Agric., 8(1): 20220214 **(11 pages).**

Sekaran, U.; Lai, L.; Ussiri, D.A.N.; Kumar, S.; Clay, S., (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review. J. Agric. Food Res., 5: 100190: 1-10 **(10 pages).**

Septiadi, D.; Hidayati, A.; Danasari, I.F.; Mundiyah, A.I., (2023). The Impact of socio-economic environment of maize farmers in supporting sustainable agriculture in the Mandalika special economic zone. IOP Conference Series: Earth Environ. Sci., 1253 012090 **(8 pages)**.

Shenkut, A.; Tesfaye, K.; Abegaz, F., (2013). Determination of water requirement and crop coefficient for sorghum (*Sorghum bicolor L.*) at Melkassa, Ethiopia. Sci. Technol. Arts Res. J., 2(3): 16-24 **(9 pages).**

Sihono; Soeranto, H.; Wijaya, M.I.; Marina, Y.M.; Puspitasari, W.; Wahyono, T., (2019). Exploring the potential of sorghum for food, animal feed, and bioenergy through induced mutation breeding. Conference: International Conference on Nuclear Capacity Building, Education, Research and Applications (I-Concern'19). Yogyakarta, Indonesia (I-Concern'19) **(7 pages).**

Singh, S.; Bhat, B.V.; Shukla, G.P.; Singh, K.K.; Gehrana, D., (2018). Variation in carbohydrate and protein fractions, energy, digestibility, and mineral concentrations in stover of sorghum cultivars. Tropic. Grassland For. Trop., 6(1): 42–52 **(11 pages).**

Sriagtula, R.; Kartib, P.D.M.H.; Abdullah L.; Supriyanto; Astuti, D.A., (2017). Nutrient changes and in vitro digestibility in the generative stage of M10-BMR sorghum mutant lines. Media Peternakan: J. Anim. Sci. Technol., 40(2): 111-117 **(7 pages).**

Sulewski, P.; Kłoczko-Gajewska, A.; Sroka, W., (2018) Relations between agri-environmental, economic and social dimensions of farms' sustainability. Sustainability. 10: 4629 **(23 pages)**.

Thawaro, N.; Toomsan, B.; Kaewpradit, W., (2017). Sweet sorghum and upland rice: alternative preceding crops to ameliorate ethanol production and soil sustainability within the sugarcane cropping system. Sugar Technol., 19(1): 64–71 **(8 pages).**

Tugga, S.E.; Hassan, A.A.; Ojeleye, O.A., (2023). Profitability analysis of sorghum small-scale farmers in selected local government areas of Gombe State, Nigeria. J. Agripreneurship Sustainable Dev., 6(1): 1-9 **(9 pages).**

USDA, (2022). Grain: world markets and trade. Washington, Disponívelem. United States Department of Agriculture **(46 pages).**

Widodo, S.; Triastono, J.; Sahara, D.; Pustika, A.B.; Kristamtini; Purwaningsih, H.; Arianti, F.D.; Praptana, R.H.; Romdon, A.S.; Widyayanti, S.S.; Fadwiwati, A.Y.; Muslimin, (2023). Economic value, farmers' perception, and strategic development of sorghum in Central Java and Yogyakarta, Indonesia. Agriculture. 13(516): 1 – 22 **(22 pages).**

Yan, P.; Song, Y.H.; Zhang, K.Y.; Zhang, F.; Tang, Y.J.; Zhao, X.N.; Wang, N.; Ke, F.L.; Gao, F.J.; Li, J.H.; Li, J.X.; Gao, Y., Yang, W.; Gao, F.C.; Qi, D.D.; Wang, Z.; You, G.X.; Han, F.X.; Zhou, Z.Y.; Li, G.Y., (2023). Interaction of genotype-ecological type-plant spacing configuration in sorghum [*Sorghum bicolor* (L.) Moench] in China. Front. Plant. Sci., 13:1-17 **(17 pages).**

Zomer, R.J.; Coe, R.; Trabucco, A.; Place, F., (2014). Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Work. Paper No. 179. World Agroforestry Centre **(72 pages).**

Zhuang, Z.; Shu, W.; Li, Z.; Liao, B.; Li, J.; Shao, J., (2009). Removal of metals by sorghum plants from contaminated land. J Environ Scie (China), 21(10):1432-1437 (**6 Pages**).

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ORIGINAL RESEARCH ARTICLE

Capital formation and production of carbon emissions in low-carbon development

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aims to examine the endogenous variable, low-carbon development, and valuate its influencing factors, given its pivotal role in environmental protection amid climate change concerns and economic growth. Low carbon development is a new platform to maintain economic growth through reducing carbon emissions and reducing the use of natural resources, because it was predicted that reducing emissions will increase economic growth while preventing forest loss, improving air quality and living standards, and reducing mortality rates.

METHODS: Utilizing a quantitative method, this study integrates a novel viewpoint by combining low-carbon development with related emission factors. The study utilizes secondary data, specifically time series data spanning 31 years from 1991 to 2021, which were analyzed using regression study methods. The factors being examined include capital formation, deforestation, land transportation, agricultural land, and industrialization.

FINDINGS: Findings reveal that low-carbon development in North Sumatra is influenced significantly by capital formation, deforestation, agricultural land, and industrialization, with land transportation showing no substantial impact. Capital formation has a favorable impact on low-carbon development. But, deforestation, land transportation, agricultural land and industrialization have a negative impact on low-carbon development. Together, these determinants account for 77.55 percent of the variance. Capital formation contributes 19.8 percent, deforestation 15.6 percent, agricultural land 19.0 percent, and industrialization 18.9 percent to low-carbon development.

CONCLUSION: The hypothesis established in this study is accepted. To foster low-carbon development in North Sumatra, specific attention is required from local governments. Capital formation is vital. Measures include controlling interest rates, supporting businesses, fostering an investment-friendly climate, ensuring security, and integrating environmental sustainability considerations into project implementation to curb carbon emissions. Prevention of deforestation involves tightening land clearance licenses and enhancing institutional quality through environmental protection and property rights legislation. The government must strive for promoting eco-friendly agricultural practices with mitigated through outreach programs involving experts who educate farmers on minimizing emissions, reducing carbon emissions from pesticide with using biochar sourced from empty palm fruit bunches and also rice straw which is very easy to obtain at a low cost and is environmentally friendly, and emphasizing environmental preservation policies in the industrial sector like industrial transformation efforts with an effective approach to reducing carbon emissions such as restructuring various aspects of industrial activities, including investment, final demand, intensity and production methods. The implementation of tax emissions and strategic interventions increases the likelihood of realizing low-carbon development in North Sumatra, aligning with sustainable development goals.

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INTRODUCTION

Low carbon development is a crucial initiative supporting sustainable development goals, as outlined by the Ministry of National Development Planning/Bappenas in 2020 (Kementerian PPN/Bappenas, 2020). This innovative approach serves as a foundation for sustaining economic and social growth by curbing carbon emissions and minimizing natural resource utilization. The essence of a low-carbon economy lies in achieving higher economic output while reducing resource consumption, resulting in a decline in greenhouse gas (GHG) emissions (Yan *et al*., 2019). Indonesia has embarked on a development policy emphasizing the equilibrium between economic advancement, social stability, and emission reduction. The government has assiduously honored its international obligation to reduce GHG emissions under the United Nations Framework Convention on Climate Change (UNFCCC) since 1992, strengthened by Law No. 6 of 1994 and subsequently Law No. 17 of 2004. Indonesia's proactive participation in addressing climate change challenges is paramount due to the nation's significant natural resources and expansive forests, vital for absorbing carbon emissions. Achieving low-carbon development and societal prosperity requires crucial support, particularly in the form of capital formation. Capital plays a pivotal role in these efforts, given the substantial financial resources needed for successful program implementation (Mulugetta and Urban, 2010). The shift toward low-carbon development necessitates significant investments, and financial size and quality are critical variables in this process. Government involvement in financing is essential to enhance the effectiveness of these activities (Dzikuc *et al*., 2021). Paradoxically, the abundance of natural resources, often viewed as an asset for governments, can hinder low-carbon development due to potential environmental harm, such as deforestation. Ignoring these concerns could lead to losses surpassing the benefits obtained. Responsible resource utilization, considering the environmental impact, is essential to ensure sustainable low-carbon development initiatives.

Chen *et al*., (2020) have highlighted that capital formation serves as a key green production factor in measuring the low carbon development index. More capital formation and investment are integral to achieving low carbon development (Dzikuc *et al*., 2021). In the context of capital formation, some sectors and types of projects have greater potential to contribute to carbon emissions in low-carbon development scenarios such as heavy industry, fossil energy, transportation, agriculture and construction. In order to achieve low-carbon development, it is crucial to generate capital formation or investment in industries that support sustainable solutions and lower carbon emissions including capital formation in renewable energy, clean technology, sustainable transportation and environmentally friendly business practices. The sources of carbon emissions are diverse (Kementerian PPN/Bappenas, 2020), encompassing sectors like agriculture, energy, transportation, and various other emission factors. Furthermore, studies by (Tian *et al*., 2019; Raihan, 2023) highlight the role of industrialization, agriculture, energy, transportation, and several other elements in contributing to carbon dioxide emissions, creating barriers to low-carbon development. Initiatives on various sources of emissions, i.e. industrial sector, have an impact not only on low-carbon development, but also on various aspects such as water pollution from industrial waste disposal and also pose a threat to marine life and humans, considerable attention to this issue is necessary. In the context of North Sumatra for the period 2016_2021, the following data outlines variables believed to influence low-carbon development. Table 1 lists the factors considered to affect low-carbon development in North Sumatra.

Factors contributing to carbon emissions significantly impact low-carbon development efforts. Transportation, necessary for economic activities, facilitates the seamless flow of products and services. However, the rising number of vehicles leads to increased carbon emissions, posing threats to both health and the environment. Similarly, agriculture, essential for economic growth and community welfare through food security, also adds to carbon emissions due to the use of various pesticides and fertilizers. Industrialization also plays a role in carbon emissions, with machines in production processes emitting smoke from factories. Essentially, for successful low-carbon development, the government must possess large capital, evidenced by strong capital formation, enabling the

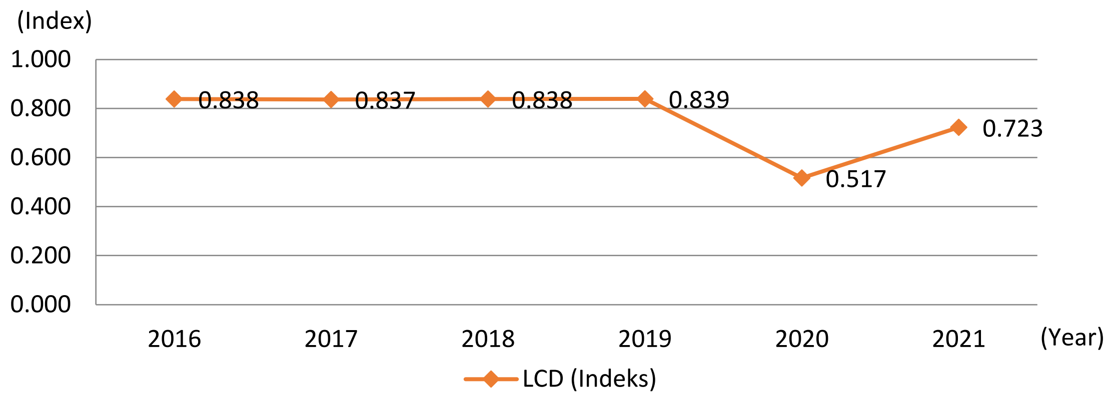

Fig. 1 : The development of low-carbon development in North Sumatera in 2016 to 2021 (Badan Pusat Statistik, 2021)

Table 1: Determinants of low-carbon development in North Sumatra in 2016_2021 (Badan Pusat Statistik, 2021)

Year	Capital formation(%)	Deforestation (%)	Land transportation (%)	Agricultural land (%)	Industrialization (%)
2016	15,57	- 52,99	16,71	13,28	5,05
2017	135,80	132,13	4,35	11,57	2,31
2018	- 28,35	- 67,54	- 77,20	- 58,69	3,66
2019	135,90	69,45	- 67,93	1,22	1,23
2020	- 7,90	- 90,05	6,41	- 5,94	- 0,84
2021	3,62	170,67	- 45,72	1,44	1,43

realization of planned programs and initiatives. Low carbon development represents a developmental approach that harmonizes population growth, economic progress, and environmental preservation. It focuses on generating increased economic productivity utilizing less natural resources and reducing environmental pollution (Yuan *et al*., 2011). This sustainable economic development model, as outlined by Ravago *et al*., (2015), strikes a balance in managing capital, human resources, and natural resources, incorporating elements of the social environment, institutions, and economic policies. Sambodo *et al*., (2022) emphasize that low-carbon development not only aims to reduce emissions but also strives to improve economic growth and lessen poverty. Their study predicts that emission reduction leads to increased economic growth while simultaneously preventing forest loss, enhancing air quality, improving living standards, and reducing mortality rates. This justification emphasizes the idea of low-carbon development as a critical strategy that supports sustainable development goals. It emphasizes the importance of fostering economic growth while simultaneously safeguarding the environment for the well-being of future generations. Carbon emissions, a global problem, are disrupting the delicate ecological balance, leading to negative consequences like heightened greenhouse gas emissions, which fuel global warming and climate change. The swift pace of economic advancement poses a threat to both human and environmental sustainability. An excellent illustration of this is the growing need for fossil fuels, coupled with high carbon emissions, which has created an energy crisis and intensified the problem of global warming. Candrianto *et al*, (2023) explained to make efforts to save the environment, must have an understanding, action related knowledge is knowledge of the impact of behavior on the environment, knowledge of tools for how to reduce environmental impact. Low-carbon development, as highlighted by Airey and Krause, (2017), is a critical tactic meant to propel substantial economic and social advancement while addressing the issues of climate change. However, the expansion of agricultural land (Jebli and Youssef,

2017) leads to increased usage of fuel-powered agricultural equipment, irrigation pump machines, and fertilizers (Samimi *et al.,* 2023), all contributing significantly to carbon emissions. Su *et al*., (2023) argue that agricultural operations exacerbate these emissions, impeding low-carbon development. To mitigate this, adjustments, such as adopting green transportation methods, as suggested Su *et al*., (2012), are crucial. Dzikuc *et al*., (2021) identify main sources of air pollution, including agriculture, fossil fuel combustion, transportation, waste management, and industrial and domestic activities, highlighting the need for efficient control methods. Emphasizing the need for a low-carbon society, (Chen *et al*., 2020) stress the objective of combating climate change, enhancing environmental protection, and ensuring energy security. Progress in low-carbon development is gauged by evaluating the qualitative contributions of economic growth, represented by the inclusion of total green production variables into the assessment process utilizing Eq. 1 (Chen *et al*., 2020).

$$EG = QG + FG \qquad (1)$$

where
EG : economic growth
QG : quality growth
FG : factor growth

The equation mentioned above clarifies that the total quality contribution of green production factors serves as a fundamental criterion for evaluating whether an economy has attained low-carbon development. This assessment is made by comparing the quality contribution (QG) to the factor contribution (EG), with a threshold set at QG/EG > 0.5. To quantify low carbon development, index numbers in the equation are utilized as a reliable metric Eq. 2 (Chen *et al*., 2020).

$$\text{LCD Index} = [QG/(QG + FG)] \qquad (2)$$

where
LCD : low-carbon development
QG : quality growth
FG : factor growth

The-low carbon development index in the equation not only indicates that a country has moved toward a low carbon economy when the index value exceeds the threshold of 0.5 but also serves as a measure of the extent of low carbon development achieved. However, it is imperative that this development remains firmly grounded in sustainable development principles, aiming to harmonize ecological concerns with the objectives of economic growth and social equity (Mulugetta and Urban, 2010). The realization of low-carbon development is accompanied by several obstacles, including sociocultural, economic, technological, and governmental barriers (Sambodo *et al*., 2022). Moreover, Onyinye *et al*., (2017) posit that the Harrod_Domar growth model underscores the importance of substantial investments to propel economic growth in a positive trajectory, necessitating countries to redirect resources from current consumption toward capital formation. Arrow and Romer, noted in (Wang *et al*., 2021), support the notion that investment plays an essential role in stimulating a nation's economic development, as per the endogenous growth hypothesis. Likewise, with low-carbon development, capital formation is very influential. Reducing emissions by using new technology certainly requires enough funding. New technology can increase energy efficiency in production processes which in turn can reduce carbon emissions. This will promote the use of clean and renewable energy such as solar panels, wind turbines and other energy resources as a replacement for fossil fuels (Samimi and Moghadam, 2024). New technology will also help with sustainable green production processes which include the use of more environmentally friendly raw materials, efficient production processes and better recycling methods (Moghadam and Samimi, 2022). Deforestation poses a serious threat to low-carbon development, contributing to climate change through carbon emissions, particularly during forest fires (Raihan and Tuspekova, 2022). Achieving sustainable development requires striking a balance between economic progress and environmental preservation, with efforts focused on minimizing deforestation to prevent natural disasters (Raihan and Tuspekova, 2022). Furthermore, Begum *et al*., (2020) emphasize the negative effect of carbon emissions resulting from deforestation and forest degradation on the global climate system. Notably, deforestation exacerbates carbon dioxide emissions, posing a direct hindrance to low-carbon development. The transportation sector also significantly influences low-carbon development, with studies by (Tang *et al*., 2015; Sporkmann *et al*., 2023; Xia *et al*., 2019) highlighting its contribution to carbon emissions. The level of carbon emissions from transportation is contingent upon factors such as transportation frequency and fuel efficiency. Thus, it is imperative to focus on increasing transportation capacity and maximizing its utilization to promote low-carbon development effectively. The transportation sector serves as a major global source of carbon dioxide emissions, contributing significantly to climate change and posing substantial health risks, especially in densely populated areas. The increase in vehicle frequency, driven by economic growth, has led to ecological challenges such as exhaust emissions, energy consumption, and noise pollution, alongside greater social issues (Li *et al*., 2023). To address these issues, policies must be developed and implemented, including fuel-saving standards, the promotion of new energy vehicles, and fiscal incentives (Chun *et al*., 2020). These actions are required for reducing fossil fuel usage and greenhouse gas emissions. Carbon dioxide emissions in the transportation sector are influenced by various factors, including transportation activities, capital structure, energy intensity, and carbon content in fuel. Transportation activity, comprising total transportation demand based on demographics, travel levels, and the number of trips, is further impacted by the ease of transportation, affecting travel rates and trip frequency (Kii *et al*., 2023). The expansion of agricultural land, as highlighted Raihan *et al*., (2023), significantly contributes to environmental degradation, leading to carbon dioxide emissions and global climate change. While there is a critical need for higher agricultural productivity and improved environmental conditions in the long term, balancing these objectives is difficult. Enhanced agricultural output can alleviate poverty, boost income allocation, enhance food production, and support economic expansion. However, the use of fuel in agriculture produces carbon emissions, worsening climate change and global warming (Su *et al*., 2023). Agricultural land plays a pivotal role in the context of low-carbon development, with various carbon emissions originating from agricultural inputs such as fertilizer, pesticides, diesel, irrigation, and land cultivation. Raihan and Tuspekova, (2022) emphasize that the agricultural added value directly impacts low carbon development; an increase in agricultural output value augments carbon emission capacity and vice versa. Economic expansion and growth drive up carbon emissions from land use activities like agriculture (Begum *et al*., 2020). Recognizing this, (Lehtonen *et al*., 2022) stress the importance of curbing carbon emissions from the agricultural sector to control environmental impact while ensuring increased farmers' income. Agriculture remains a sector contributing to carbon emissions, presenting a formidable challenge to low-carbon development efforts. One of the key objectives of sustainable development is industrialization, which involves enhancing infrastructure and implementing sustainable industrial retrofits. This process aims to improve resource efficiency, promote the widespread adoption of technology, and incorporate clean and environmentally acceptable industrial practices (Keeffe *et al*., 2023). While industrialization significantly contributes to economic growth, it comes with substantial environmental challenges, including carbon emissions generated during production and fuel use. The waste produced in the industrial activities also adds to carbon emissions, harming both the environment and community welfare, eventually impeding advancement in low-carbon development initiatives. Zhang *et al*., (2019) elaborate on the influential role of industrial transformation in low-carbon development. A successful strategy for cutting carbon dioxide emissions entails restructuring various aspects of economic operations, including investment, trade, final demand, intensity, and production techniques. Industrial practices rooted in traditional methods lacking technological advancements significantly elevate carbon emissions, ultimately hindering low-carbon development and impeding progress toward sustainable goals. The relationship between industry and carbon emissions, as elucidated (Xiaoqing and Jianlan, 2011), highlights the critical role of industrial structure in emission changes. Alterations in the overall economy serve as a primary driver for emissions. Thus, changing industrial structure and improving technical efficiency become crucial techniques for emission reduction, benefiting low-carbon development initiatives. Similarly, (Tian *et al.*, 2019) demonstrate that industry influences carbon emissions and low-carbon development by optimizing production across construction, manufacturing, and service sectors. This optimization, achieved through well-managed production activities, product recycling, and the promotion of clean and renewable energy, promotes low-carbon and environmentally friendly industrial development, further aligning industrial practices with sustainable and low-carbon development objectives. This study aimed to prove the effect of determinants on low carbon development in a model. The hypothesis in this study is there is a substantial impact between capital formation, deforestation, land transportation, agricultural land, and industrialization in North Sumatra. The study is expected to compensate for the lack of research. It has been conducted in North Sumatra, Indonesia, between 2022 and 2023.

MATERIALS AND METHODS

Method of the study

This quantitative study was performed using the descriptive and associative methods. Secondary data sourced from the central statistical agency, spanning the period from 1991 to 2021, covering a total of 31 years (n), were regarded in this study. The variables under investigation included capital formation, deforestation, land transportation, agricultural land, and industrialization, all of which are factors assessed for their influence on low-carbon development.

Operational definition of the variables

Measurement of the data of each variable is displayed in Table 2. The data was collected from the documentation, annual reports or records issued by the North Sumatra Central Bureau of Statistics

As can be seen from the conceptual framework in Fig. 2, the mathematical measurements are expressed using Eq. 3 (Tian *et al.*, 2019; Raihan,

Table 2 : Operational definition of the research variables

Variable	Measurement	Unit	Institutions
Low carbon development (Y)	Index	Y	Badan Pusat Statistik, 1991-2021
Capital formation (X1)	Domestic capital formation	Billion/y	Badan Pusat Statistik, 1991-2021
Deforestation (X2)	Area of deforestation	ha/y	Badan Pusat Statistik, 1991-2021
Land transportation (X3)	The number of land transportation	No/y	Badan Pusat Statistik, 1991-2021
Agricultural land (X4)	Area of agriculture	ha/y	Badan Pusat Statistik, 1991-2021
Industrialization (X5)	GRDP in Industry sector	Billion/y	Badan Pusat Statistik, 1991-2021

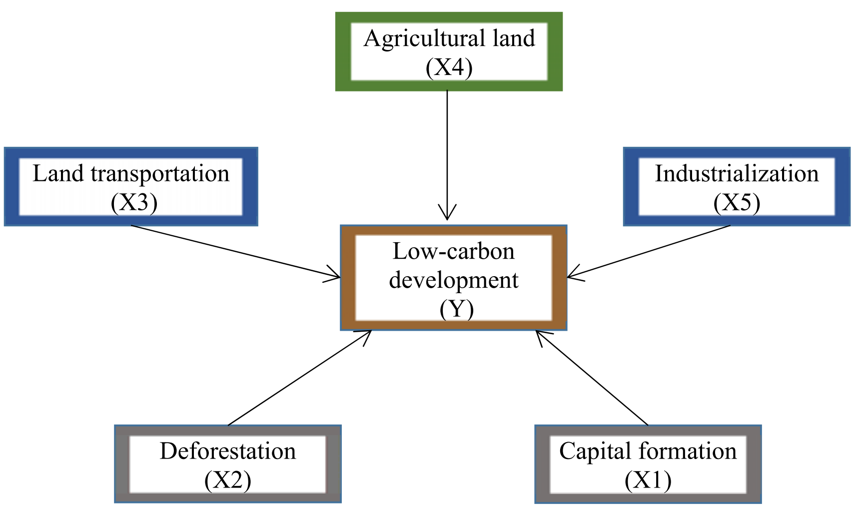

Fig. 2: The study conceptual framework

2023; Chen *et al*., 2020).

$$Y_t = \alpha_0 + \alpha_1 X_{1t} + \alpha_2 X_{2t} + \alpha_3 X_{3t} + \alpha_4 X_{4t} + \alpha_5 X_{5t} + \varepsilon_{1t} \quad (3)$$

Classic assumption test

In this study, classical assumption tests were conducted to ensure the robustness of the analysis. The normality test was performed using the Jarque_ Bera test, where the hypothesis was determined using probability values. If the probability value is > 0.05, the distribution is considered normal; conversely, if the probability value is <0.05, the distribution is considered non-normal. The multicollinearity test utilized the variant inflation factor (VIF) value, with a hypothesis stating that if the data exhibits a VIF value exceeding 10, it indicates no tolerance or multicollinearity issues. Conversely, if the VIF value is smaller than 10, the correlation between each independent variable is deemed acceptable. The heteroscedasticity test was conducted using the Glejser test. In heteroscedasticity testing, if the probability value is > 0.05, it indicates that the regression model is free from heteroscedasticity

Statistical tests

In this study, the t-test was employed to assess the significance of the effect of the exogenous variable (X) on the endogenous variable (Y). If the probability value is smaller than the predefined threshold α = 0.05, Ho (null hypothesis) is rejected, and Ha (alternative hypothesis) is accepted, suggesting a significant effect. Conversely, if the probability value is larger than α = 0.05, the null hypothesis is accepted. Additionally, the F-test was applied to assess the collective influence of the exogenous variables on the endogenous variable. If the probability value is smaller than α = 0.05, Ho is rejected, and Ha is accepted, signifying that the exogenous variables collectively exert a significant influence on the endogenous variable.

RESULTS AND DISCUSSIONS

The results of classical assumption test

Based on Table 3, the normality test results for the low carbon development equation (Y) indicate a Jarque-Bera value of 1.073 and a probability value of 0.584. Since the probability value (0.584) is greater than the significance level of 0.05, it can be concluded that the data follows a normal distribution. Stated differently, the data in the low-carbon development equation for this study is normally distributed.

The multicollinearity test is seen from the VIF value as presented in Table 4.

Based on the findings of the multicollinearity test in the low-carbon development equation, it is clear that the VIF values for each variable are significantly below 10. Specifically, the VIF value for the capital formation variable is 2.924, deforestation variable is 3.814, land transportation variable is 2.058, agricultural land variable is 1.336,

Table 3 : Normality test results

Notes	Score
Mean	3.720016
Median	1.780015
Maximum	1.150014
Minimum	1.420014
Std. dev.	5,460015
Skewness	0l317179
Kurtosis	3.654850
Jarque-Bera	1.073684
Probability	0.584592

Table 4: The results of multicollinearity test

Variable	Coefficient variance	Uncentered VIF	Centered VIF
Capital formation (X1)	8.080031	118.8117	2.924719
Deforestation (X2)	7.940031	74.71421	3.814240
Land transportation (X3)	5.110037	5.353902	2.058448
Agricultural land (X4)	7.670035	36.98119	1.336093
Industrialization (X5)	1.100030	96.84405	2.492157

Table 5: The results of heteroscedasticity test

F-statistic	0.641064
Prob.F(5,25)	0.6706

Table 6 : The results of the equation measurement

Variable	Coefficient	S.E.	T-statistic	Probability	R-squared	F-statistic	Prob (F-statistic)
C	1.400014	2.390014	0.588006	0.5618	0.755544	4.540029	0.000000
Log(Y2)	2.110015	8.990016	2.336947	0.0278			
Log(Y3)	- 2.333315	8.910016	- 2.611337	0.0150			
X1	- 1.150018	7.150019	- 1.611733	0.1196			
X2	2.430017	8.760018	2.777479	0.0102			
Log(X3)	- 1.001120	1.050015	- 9.550014	0.0000			

Table 7 : The partial contribution results

Variable	Standardized coefficients Beta	Correlation	Contribution
X1	0,127	1,181	19,86
X2	0,302	0,391	15,63
X3	0,178	0,09	2,12
X4	0,251	0,573	19,04
X5	0,292	0,489	18,90

and industrialization variable is 2.492. Since all VIF values are less than 10, it suggests that there is no problem of multicollinearity among the independent variables in this equation. Furthermore, the heteroscedasticity test conducted using the Glejser test is presented in Table 5.

Based on the test results above, it can be seen that the F-statistic value is 0.641 and the probability value is 0.670, which indicates it is greater than α (alpha) at 0.05 level, or 0.670 > 0.05. This result indicates that there is no heteroskedasticity in the low-carbon development equation.

The results of hypothesis testing

The findings of the hypothesis test and the estimation of the low-carbon development equation processed using Eviews can be seen in Table 6.

Table 7 shows the partial contribution of variables to the dependent variable.

The model equation for low-carbon development derived from the estimation conducted in this study is as Eq. 4 (Tian *et al*., 2019; Raihan, 2023; Chen *et al*., 2020):

$$Y = 1.400 + 2.110\log(X1) - 2.333\log(X2) - 1.150\ (X3) + 2.430\ (X4) - 1.001\log(X5) \quad (4)$$

In this study, the alternative hypothesis poses a significant influence of capital formation, deforestation, land transportation, agricultural land, and industrialization on the low carbon development of North Sumatra. The estimation findings of the low carbon development equation show an F-statistical probability value of 0.000. When compared to the significance level (α) of 0.05, the probability value of <0.05 (0.000 < 0.05) demonstrates that capital formation, deforestation, land transportation, agricultural land, and industrialization collectively exert a significant impact on North Sumatra's low-carbon development. The constant value for low carbon development is 1.400, meaning that if the variables values capital formation, deforestation, land transportation, agricultural land, and industrialization remain unchanged, low-carbon development will increase by 1.40%. Individually, an increase of 1% in capital formation (X1) corresponds to a 2.110% rise in low-carbon development. Conversely, deforestation (X2) exhibits a negative influence, with an estimated coefficient value of -2.333, indicating that a decrease in deforestation promotes low-carbon development. Similarly, land transportation (X3) and industrialization (X5) exhibit negative effects with coefficient values of -1.150 and

1.001, respectively. Conversely, agricultural land (X4) has a beneficial impact, with a coefficient of 2.430. These findings highlight the variables' contributions to North Sumatra's low-carbon development under the ceteris paribus assumption. In the pursuit of achieving low-carbon development, adequate funding is necessary for implementing ecofriendly initiatives, which inherently incur higher costs compared to conventional or non-environmentally friendly activities. Government bodies and policy-makers require significant funding to create and sustain these initiatives. This relationship between capital formation and low-carbon development is unidirectional, as capital plays an essential role in enabling the shift to eco-friendly practices (Mulugetta and Urban, 2010). Capital formation has synergy with reducing carbon emissions such as sustainable investment. Allocating capital to sustainable and environmentally friendly projects can yield long-term financial rewards while reducing environmental consequences including investments in renewable energy, energy efficiency and other environmentally friendly technologies. Apart from that, strong capital can support technological innovation, sustainable waste management, and various other carbon emission reduction programs. The importance of financial size and quality in facilitating this shift cannot be exaggerated. Ikhsan and Satrianto, (2023) highlights gross fixed capital formation in the form of capital goods is able to encourage investment allocation and have an impact on the growth of productive sectors which can spur economic growth. Enormous investments, especially in areas such as human resources, are necessary for the effective implementation and upkeep of sustainable low-carbon development initiatives (Dzikuc *et al*., 2021). Several economic concepts and theories can help how interventions are designed to drive change toward a low-carbon economy. This can be realized through carbon price or carbon tax, incentives and subsidies, technological innovation, understanding consumer behavior to design promotional models, business desires, and regulations so that effective interventions can be accepted at the economic and societal levels, helping to achieve the goal of sustainable capital formation and low-carbon emissions. Deforestation poses a critical threat to low-carbon development. This damaging activity reduces forest cover, diminishing the number of plants available to absorb carbon dioxide and produce necessary oxygen. As deforestation spreads, the decrease in carbon-absorbing plants leads to a rise in carbon emissions. Begum *et al*., (2020) underscore the noteworthy influence of deforestation on low-carbon development. Addressing this issue is crucial for sustainable development and supporting low-carbon activities. Lowe, (2014) highlights the necessity of reducing carbon emissions resulting from deforestation and forest degradation to bolster sustainable development efforts and support low-carbon practices effectively. Adequate funding and strategic interventions are essential in curbing deforestation and enabling the shift toward a more environmentally friendly, low-carbon future. Land transportation stands as a major source of carbon emissions, impeding advancement in low-carbon development. Emissions from vehicles, primarily exhaust gases, result in harmful air pollution. Futhermore, the use of fuel not only escalates energy consumption but also leads to increased carbon emissions. The rise in the number of vehicles directly correlates with heightened carbon emissions, thereby hindering low-carbon development efforts. The study findings, as indicated (Kii *et al*., 2023), align with this perspective, showing that the reduction in transportation-related carbon emissions stems from a decrease in population and improved fuel efficiency. For instance, in 1998, transportation increased by 3.32%, coinciding with a boost in low-carbon development. However, fuel consumption dropped by 0.92 throughout the same period. Similarly, in 2009, despite a 9.35% rise in transportation, fuel use decreased by 7.17%. Improving fuel efficiency can mitigate vehicle emissions by using higher-quality fuel, leading to reduced consumption. The intensity of travel significantly impacts fuel efficiency and ultimately curtails carbon emissions. Notably, population size serves as one important element affecting carbon dioxide emissions from the transportation sector. Strategies such as maintaining population density and curtailing vehicle use are crucial efforts to mitigate carbon emissions and promote low-carbon development. The major impact of agricultural operations on North Sumatra's low-carbon development is evident, where changes in agricultural land directly influence the region's low-carbon progress. Research (Su *et al.*, 2023) highlights that agricultural practices contribute to increased carbon emissions, presenting a challenge for low-carbon development. The growth of the agricultural industry intensifies the use of machinery and workforce, increasing emissions. Emissions from fertilizer use, crop residue burning, and flooded rice cultivation further compound the issue as well (Sapkota *et al.*, 2021). The long-term use of pesticides in agriculture will threaten the quality of soil and water resources. Yavari *et al.,* (2022) explained that biochar is a carbon-rich biosorbent which can be used as a medium to stabilize organic substances in the soil. It is sustainable and affordable as it can be made from locally accessible waste from empty palm fruit bunches and rice husks. So, biochar has the potential to reduce emissions from the agricultural sector to the environment with the concept of controlling pesticides which of course can increase the commercial value of biochar. Furthermore, industrialization, particularly in the construction industry, emerges as a significant contributor to carbon dioxide emissions. Satrianto and Juniardi, (2023) explained industrialization growth will have an impact on reducing the quality of the environment and when it reaches a high economic level but is not environmentally friendly, it will result in an increase in carbon emissions which will have an impact of air pollution, decreased air quality and opening up of new land which, if done using traditional methods through burning, will cause environmental damage. The main driver of climate change and global warming is GHG including carbon dioxide, several countries have implemented a tax-based carbon pricing system with lower rates for certain industries and which produces fewer emissions. The emission trading system mechanism is a strategy to improve economic incentives and decrease emissions by establishing pollution restrictions. This mechanism is designed to be environmentally friendly and economical as a driver of the low-carbon economic transition, it has benefit for industry because it offers emissions monitoring, stringent fines for infractions and high compliance. Tian *et al*., (2019) emphasize the industrial sector's significant contribution to emissions, exacerbated by fuel usage and high-intensity machinery, hindering low-carbon development efforts. Raihan *et al.,* (2023) underline that increasing industrialization raises carbon emissions, further exacerbated by industrial waste and insufficient energy-saving measures. Juniardi *et al*, (2002) highlight so that government provides supporting technology environmentally friendly industry to support green industrial programs. Resolving these issues is imperative for reducing emissions and encouraging sustainable, low-carbon development in North Sumatra.

CONCLUSION

Based on the study findings, it is evident that capital formation, deforestation, agricultural land, and industrialization significantly influence low-carbon development in North Sumatra, collectively explaining 75.55% of the variance (R-square 0.7555). Specifically, capital formation contributes 19,8%, deforestation 15,6%, agricultural land 19,0%, and industrialization 18,9% to low-carbon development, while land transportation does not exhibit a significant influence of 2,12%. To promote low-carbon development effectively, the regional government must adopt targeted policies addressing each factor. Capital formation is essential in accelerating economic growth and achievinglow-carbon development. Policies such as interest rate control and support for investor-focused businesses are essential, alongside ensuring an investor-friendly climate and security measures. Additionally, environmental sustainability should be a priority in project realization to curb carbon emissions. Deforestation mitigation measures, including stricter permits for land clearing, improved environmental regulations, and forest area preservation, are vital. Next, is attention to forest preservation, particularly protected forests, so that they are maintained for cleaner air and maximum absorption of carbon dioxide. Apart from absorbing carbon emissions, forests can also maintain the diversity of flora and fauna and also save the Earth from natural disasters caused by reduced forest cover such as landslides and floods. In addition, it must improve the standard of institutions, such as enforcing strict penalties against those who persist in engaging in activities to diminish the area of tree cover resulting in widespread deforestation which harms many people and impedes low-carbon development. To reduce carbon emissions in land transportation, it is necessary to implement policies and actions that support the use of low-emission vehicles such as electric vehicles, vehicle emissions regulations by using biodiesel and others as an alternative to fossil fuels and restricting vehicles in certain zones, supporting environmentally friendly public transportation, as well as public education and awareness. In the agricultural sector, ecologically sustainable practices should be promoted. Agricultural activities, contribute to carbon emissions, so the government must also pay attention to the agricultural techniques applied. Agriculture as one of the industries that contributes to GRDP certainly cannot be disregarded even though it is a contributor to carbon emissions as a barrier to low-carbon development. However, the government must strive for environmentally friendly agricultural techniques with mitigated through outreach programs involving experts who educate farmers on minimizing emissions. To reduce carbon emissions originating from the use of pesticides in agriculture which contaminates water and soil, this can be done by using biochar made from empty palm fruit bunches and also rice straw which is easily obtained at a low cost and is environmentally friendly. Industrial sector policies aimed at environmental preservation are paramount, increasing the likelihood of achieving sustainable low-carbon development in North Sumatra, aligning with the region's sustainable development goals. Industrial transformation efforts with an effective approach to reducing carbon emissions such as restructuring various aspects of industrial activities, including investment, trade, final demand, intensity and production methods. Then the government also provides environmentally friendly industry supporting technology to support the green industry program. Maximize production in the construction, manufacturing and service industries for effective carbon dioxide reduction, for example, by managing production operations well, using recyclable product, and supporting clean and renewable energy sources. The implementation of tax emissions can also be carried out by considering certain industries and industries that produce fewer emissions and setting emission limits. This is very beneficial to the sector to integrate emissions, penalties for infractions, and increased compliance from associated parties.

AUTHOR CONTRIBUTIONS

E.S. Siregar helped in the design and development of models in the study, collection and analysis of data, and creation of study reports. S.U. Sentosa guided and mentored the literature review. A. Satrianto accompanied and guided the writing of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication, and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
+	Plus sign
=	Equal sign
>	Strict inequality (greater than)
-	Minus sign
/	Per
Α	Alpha
Ε	Error term
EG	Economic growth
Eq	Equation
et al.	Et alia
F	Simultaneous
Fig.	Figure
FG	Factor growth
GHG	Greenhouse gas
GRDP	Gross regional domestic product
Ha	Hectare
LCD	Low carbon development
Log	Logarithm
No	Number
Prob	Probability
QG	Quality growth
R^2	Correlation coefficient
S.D.	Standard deviation
S.E.	Standard error
T	Time
UNFCCC	United nations framework convention on climate change
Var	Variable
VIF	Variance inflation factor
X1	Capital formation
X2	Deforestation
X3	Land transportation
X4	Agricultural land
X5	Industrialization
y	Year
Y	Endogenous variable

REFERENCES

Airey, S.; Krause, T., (2017). Georgetown ain't got a tree. We got the trees"-amerindian power and participation in guyana's low carbon development strategy. Forests. 8(3): 1–24 **(24 pages).**

Begum, R.A; Raihan, A.; Said, M.N.M., (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in malaysia. Sustainability. 12(22):1–15 **(15 pages).**

Candrianto, C.; Aimon, H.; Sentosa, S.U., (2023). The role of knowledge, awareness and environmental attitudes in green product management. Global J. Environ. Sci. Manage, 9(1):101–112 **(12 pages).**

Chen, Y.; Liu, S.; Wu, H.; Zhang, X.; Zhou, Q., (2020). How can belt and road countries contribute to glocal low-carbon development? J. Cleaner Prod., 256(120717): 1-13 **(13 pages).**

Chun, T.X.; Yuan, Z.; He, G.B.; Jie, T.; Dong, W.; Xin, G.J., (2020). Assessment of the macro-economic impacts of low-carbon road transportation policies in chongqing, china. Adv. Clim. Change Res., 11(4): 429–441 **(13 pages).**

Dzikuc, M.; Wyrobek, J.; Popławski, T., (2021). Economic determinants of low-carbon development in the visegrad group countries. Energies. 14(13): 1–12. **(12 pages).**

Jebli, M.Ben; Youssef, S.Ben; (2017). The role of renewable energy and agriculture in reducing co2 emissions: evidence for north africa countries. Ecol. Indic., 74:295–301 **(7 pages).**

Juniardi, E.; Amar, S.; Aimon, H., (2022). Panel data regression approach on inclusive green growth. Global J. Environ. Sci. Manage., 8(4): 533-544 **(12 pages).**

Ikhsan, A.; Satrianto, A., (2023). The effect of financial development on economic growth in high-income countries. Asian Econ. Financ. Rev., 13(3): 202-215 **(14 pages).**

Keeffe, S.O.; Sullivan, D.O.; Bruton, K., (2023). Development of a modelling tool to aid the transition to carbon neutral industrial manufacturing. J. Cleaner Prod., 425(138604) : 1-19 **(19 pages).**

Kementerian PPN/Bappenas, (2020). 7 Proyek implementasi pembangunan rendah karbon indonesia. Kementerian PPN/Bappenas. 1-24 **(24 pages).**

Kii, M.; Isikawa, R.; Kometani, Y., (2023). Toward a carbon neutral urban transportation system in japan. IATSS Res., 47(2):171–178 **(8 pages).**

Lehtonen, H.; Niemi, E.H.; Niemi, J., (2022). The transition of agriculture to low carbon pathways with regional distributive impacts. Environ. Innovation Soc. Transitions.

44 :1–13 **(13 pages).**

Li, X.; Zhan, J.; Lv, T.; Wang, S.; Pan, F., (2023). Comprehensive evaluation model of the urban low-carbon passenger transportation structure based on dpsir. Ecol. Indic., 146(109849): 1-14 **(14 pages).**

Lowe, S., (2014). Can mining be part of a low-carbon, low-deforestation development strategy? The case of guyana. Environ: Sci. Policy Sustainable Dev., *56*(3): 4–11 **(8 pages).**

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages).**

Mulugetta, Y.; Urban, F., (2010). Deliberating on low carbon development. Energy Policy. 38(12): 7546–7549 **(4 pages).**

Onyinye, N.G.; Idenyi, O.S.; Ifeyinwa, A.C., (2017). Effect of capital formation on economic growth in nigeria. Asian J. Econ. Bus. Account., *5*(1):1–16 **(16 pages).**

Raihan, A., (2023). The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the philippines. Energy Nexus. 9(100180): 1-12 **(12 pages).**

Raihan, A.; Tuspekova, A., (2022). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: new insights from kazakhstan. World Develop. Sustainability. 1(100019): 1-17 **(17 pages).**

Ravago, M.L.V.; Balisacan, A.M.; Chakravorty, U., (2015). The principles and practice of sustainable economic development: overview and synthesis. Sustainable Econ Develop: Resour. Environ. Inst.,3-10 **(8 pages).**

Sambodo, M.T.; Yuliana, C.I.; Hidayat, S.; Novandra, R.; Handoyo, F.W.; Farandy, A.R.; Inayah, I.; & Yuniarti, P. I. (2022). Breaking barriers to low-carbon development in indonesia: deployment of renewable energy. Heliyon. 8(4): 1-11 **(11 pages).**

Samimi, M.; Moghadam, H., (2024). Investigation of structural parameters for inclined weir-type solar stills, Renew. Sustain. Energy Rev., 190: 113969 **(10 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Sapkota, T. B.; Khanam, F.; Mathivanan, G.P.; Vetter, S.; Hussain, S.G.; Pilat, A.L.; Shahrin, S.; Hossain, M.K.; Sarker, N.R.; Krupnik, T.J., (2021). Quantifying opportunities for greenhouse gas emissions mitigation using big data from smallholder crop and livestock farmers across bangladesh. Sci. Total Environ., 786(147344): 1-16 **(16 pages).**

Satrianto, A; Juniardi, E., (2023). Inclusive human development and inclusive green growth : a simultaneous approach. Int. J. Sustainable Dev. Plann., 18(2): 523-530 **(8 pages).**

Siregar, E.S.; Sentosa, S.U.; Satrianto, A., (2023). An analysis on the economic development and deforestation. Global J. Environ. Sci. Manage., 10(1):355–368 **(14 pages).**

Sporkmann, J.; Liu, Y.; Spinler, S., (2023). Carbon emissions from european land transportation: a comprehensive analysis. Transport. Res.: Transport. Environ., 121: 1-10 **(10 pages).**

Statistik, B.P.; (2021). Sumatera utara dalam angka. Medan. Badan Pusat Statistik

Su, L.; Wang, Y.; Yu, F., (2023). Analysis of regional differences and spatial spillover effects of agricultural carbon emissions in china. Heliyon. 9(6): 1–17 **(17 pages).**

Su, M.; Liang, C.; Chen, B.; Chen, S.; Yang, Z., (2012). Low-carbon development patterns: observations of typical chinese cities. Energies. 5(2) : 291–304 **(14 pages).**

Tang, S.; Wang, W.; Yan, H.; Hao, G., (2015). Low carbon logistics: reducing shipment frequency to cut carbon emissions. Int. J. Product. Econ., 164:339–350 **(12 pages).**

Tian, X.; Bai, F.; Jia, J.; Liu, Y.; Shi, F., (2019). Realizing low-carbon development in a developing and industrializing region: impacts of industrial structure change on co2 emissions in southwest china. J. Environ Manage., 233 : 728–738 **(11 pages).**

Wang, C.; Kim, Y.S.; Kim, C.Y., (2021). Causality between logistics infrastructure and economic development in china. Transport Policy. 100: 49–58 **(10 pages).**

Xia, C.; Li, Y.; Xu, T.; Chen, Q.; Ye, Y.; Shi, Z.; Liu, J.; Ding, Q.; Li, X., (2019). Analyzing spatial patterns of urban carbon metabolism and its response to change of urban size : a case of the yangtze river delta,china. Ecol. Indic., 104 : 615–625 **(11 pages).**

Xiaoqing, Z.; Jianlan, R., (2011). The relationship between carbon dioxide emissions and industrial structure adjustment for shandong province. Energy Procedia. 5: 1121–1125 **(5 pages).**

Yan, X.; Ge, J.; Lei, Y.; Duo, H., (2019). China's low-carbon economic transition: provincial analysis from 2002 to 2012. Sci. Total Environ., 650(1): 1050–1061 **(12 pages).**

Yavari, S.; Asadpour, R.; Kamyab, H.; Yavari, S.; Kutty, S.R.M.; Baloo, L.; Manan, T.S.B.A.; Chelliapan, S.; Sidik, A.B.C., (2022). Efciency of carbon sorbents in mitigating polar herbicides leaching from tropical soil. Clean Technol. Environ. Policy. 24 : 251-260 **(10 pages).**

Yuan, H.; Zhou, P.; Zhou, D., (2011). What is low-carbon development? A conceptual analysis. Energy Procedia. 5 : 1706–1712 **(7 pages).**

Zhang, S.; Li, H.; Zhang, Qi.; Tian, X.; Shi, F., (2019). Uncovering the impacts of industrial transformation on low-carbon development in the yangtze river delta. Resour. Conserv. Recycl., 150(104442): 1-10 **(10 pages).**

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ORIGINAL RESEARCH PAPER

Sustainability status of amphidromous nike fish, *postlarva Gobioidei*, in estuarine water

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ABSTRACT

BACKGROUND AND OBJECTIVES: Nike fish are a postlarvae group of gobies found in the Gobiidae and Eleotridae families. These fish are a seasonal delicacy in Gorontalo, with significant economic value and popularity among the community. Data from 2020 to 2021 showed a downward trend in Nike fish production in Gorontalo City despite ongoing efforts to promote it as a consumable fish. Therefore, this study assessed the sustainability status of Nike fish in the waters of Tomini Bay Gorontalo.

METHODS: This study was conducted across five Nike fishing locations in Tomini Bay, Gorontalo Province, namely the Bone-Bolango, Bilungala, Tombulilato, Taludaa, and Bilato estuaries, from April to September 2023. Data were collected through interviews with 109 Nike fishers and four experts from government agencies in Gorontalo Province. Meanwhile, other supporting data were obtained from various references that support the study objectives. The sustainability status analysis was conducted using rapid appraisal for fisheries, a software with an assessment method comprising five dimensions, ecological, economic, social, ethical, and technological, which are analyzed multi-dimensionally.

FINDINGS: The results showed that of the five dimensions analyzed, only one, the technological dimension, exhibited sustainability. Meanwhile, the other four dimensions, including ecology, economic, social, and ethical, showed a less sustainable status. Some attributes that significantly affected the sustainability of Nike fish resource use in the waters of Tomini Bay, Gorontalo, include fishing location, Nike diversity, by-products, profit distribution, contribution to regional revenue, dependence on subsidies, level of conflict, the role of fishermen in terms of sustainability, fish landing sites, handling on board, externalities (waste disposal), and the level of violations. The results of the multi-dimensional scaling analysis showed that the average index values of the ecological, economic, social, and ethical dimensions are 33.53, 40.33, 30.86, and 25.19, respectively, demonstrating a less sustainable status. Meanwhile, only one of the five dimensions studied has an index value of more than 50—the technological dimension. The multi-dimensional scaling index value of the technology dimension is 84.09, demonstrating its sustainable status. The stress value (0.14 to 0.15) and the coefficient of determination (0.91 to 0.94) in the multi-dimensional scaling calculation showed that the analysis carried out was appropriate.

CONCLUSION: The sustainability status of Nike fish in the waters of Tomini Bay, Gorontalo, is less sustainable and highly dependent on the environmental factors that support their life as amphidromous fish. The involvement of all stakeholder elements in implementing sustainable practices is also essential in terms of supporting sustainability. Therefore, this study provided important contributions that can be used by local governments and stakeholders to form appropriate management policies to ensure sustainability in the future. This study can provide information or insights for countries that have fishery potential similar to the waters of Tomini Bay, Gorontalo, to carry out better fisheries management.

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INTRODUCTION

Nike fish are typically small, measuring 2 to 5 centimeters (cm) in size, and found seasonally in the waters of Tomini Bay, Gorontalo City, usually at the end of the lunar cycle until the new one begins (Sahami *et al.,* 2020). The seasonal appearance and unique flavor that characterize Nike fish are highly valued and hold economic importance. Nike fish possess critical historical and cultural significance. It is biologically defined as a group of amphidromous gobies in the postlarval phase. Sahami et al. (2019b) successfully initiated the discovery of the diversity of species that made up schools of Nike fish with the discovery of four species in the Gobiidae and Eleotridae families through a molecular analysis of cytochrome oxidase subunit I (COI) mitochondrial deoxyribonucleic acid (DNA). The Gobiidae and Eleotridae families dominate amphidromous species in tropical rivers (Keith and Lord, 2011). Gobies also dominate in terms of diversity and abundance of the species present in estuary habitats (Thuy *et al.,* 2022). During the amphidromous phase, goby fish grow and reproduce in freshwater habitats (Iida *et al.,* 2017), laying their eggs on the substrate at the bottom of the river (Yamasaki *et al.,* 2011). After hatching, the larvae drift to the sea, and the juveniles travel back to the river of their parental origin after spending a while in marine waters (Maie *et al.,* 2009). The presence of this fish is strongly affected by environmental factors that occur in the three distinct aquatic ecosystems, namely freshwater, estuarine, and marine waters. The amphidromous life cycle makes this fish population vulnerable to habitat modification and connectivity in marine and freshwater environments (Franklin *et al.,* 2019). Reduced riverine vegetation contributes to the abundance and distribution of gobies, as Keith et al. (2015) explained that the amount of plant cover on river banks is an important factor for goby fish habitats. The sustainability of the fish is also primarily determined by the success of the larval recruitment process from marine habitats to freshwaters (Simanjuntak *et al.,* 2021). Larval survival and distribution are strongly influenced by environmental factors such as water flow and coastal currents (Marina *et al.,* 2021), temperature and salinity (Roman *et al.,* 2019). Food availability in the habitat is also vital in the postlarval phase (Jackson and Lenz, 2016). Ecologically, Nike fish, as amphidromous fish, play an essential role in their habitat. They occupy various levels of food webs in rivers (Schoenfuss and Blob, 2007) and estuaries (Jenkins *et al.,* 2010), influencing the distribution of fauna in these waters (Hein and Crowl, 2010). The crucial role of these fish in their habitat makes their ecological value more significant than their economic value (Zhai *et al.,* 2023). Nike fish are widely distributed in the estuarine waters of Tomini Bay, namely Gorontalo City Bay (Sahami *et al.,* 2019a), Bone estuary (Olii *et al.,* 2017), Paguyaman (Sahami and Habibie, 2021), Taludaa, Bilungala, and Tombulilato estuaries. In these diverse waters, Nike fish continue to be actively harvested and consumed, reflecting the substantial efforts devoted to its usage. The data collected on Nike fish production in Gorontalo City between 2020 and 2021 showed a consistent decline in production. This decline in production supports the hypothesis of this study that all dimensions of sustainability (ecological, economic, social, technological, and ethical) concerning the use of Nike fish resources have a less-than-sustainable status. While various studies on the eco-biology and processing of Nike fish products have been conducted in recent years, none have addressed the sustainability status of the resource. To fill this gap, a multi-dimensional method was adopted to assess the sustainability status of these resources, using the rapid appraisal for fisheries (RAPFISH) method. Originally developed for fisheries, this method has also been used to assess other fields. Alder et al. (2002) used the RAPFISH method to evaluate the sustainability of marine protected area management. Meanwhile, Martias et al. (2023) used this same method to analyze the sustainability status of healthy settlement arrangements in the Penyengat Island coastal area, which has been designated as a cultural heritage site. Evaluating sustainable usage is the basis for ensuring the balanced exploitation of fishery resources (Bi *et al.,* 2023). The main aim of this study was to assess the sustainability status of Nike fish usage in the waters of Tomini Bay. This study was conducted across five Nike fishing locations in Tomini Bay, Gorontalo Province, Indonesia, in 2023.

MATERIALS AND METHODS

This study was carried out across five specific estuaries of Nike fishing locations, namely Bone-Bolango (0°30'16.815" north: N, 123°3'44.3982" east: E), Bilungala (0°22'13.3782" N, 123°12'47.217" E), Tombulilato (0°18'34.6638" N, 123°21'35.3334"

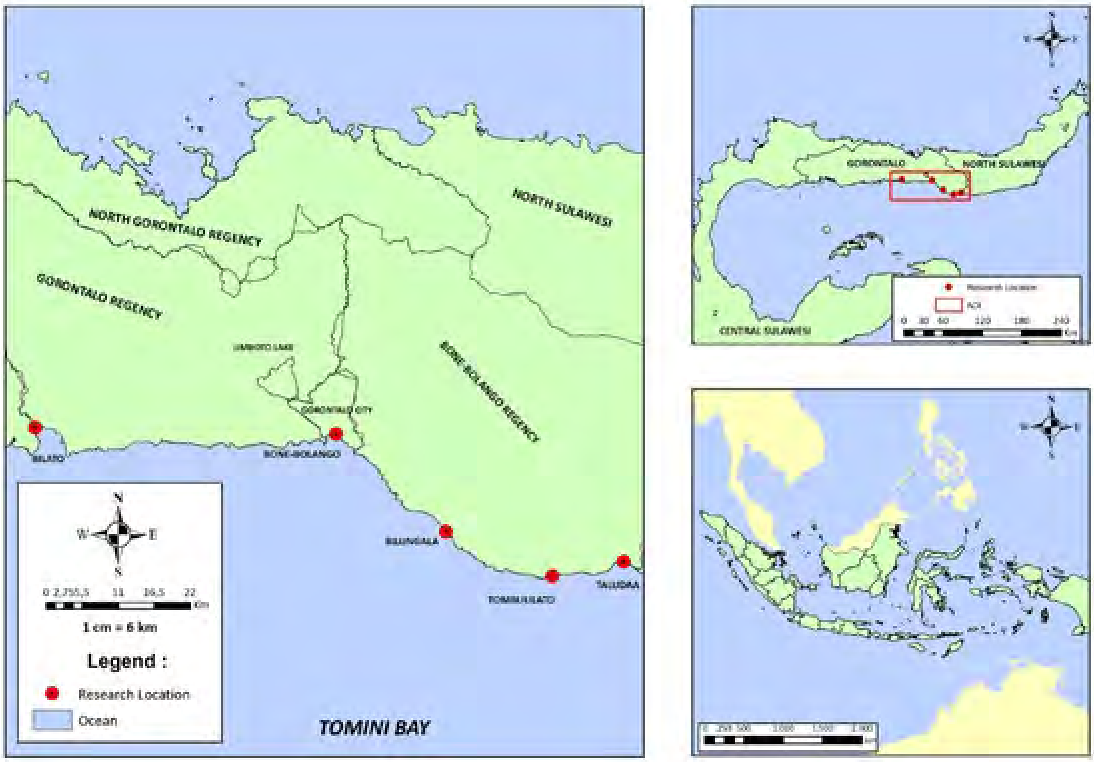

Fig. 1: Geographic location of the study area in the five specific Nike fishing locations: Bone-Bolango, Bilungala, Tombulilato, Taludaa, and Bilato estuaries, Indonesia

E), Taludaa (0°19’46.6818” N, 123°27’27.4104” E, and Bilato estuaries (0°30’49.1898” N, 122°38’57.6492” E), as shown in Fig. 1.

Data collection

This descriptive quantitative study used both primary and secondary data sources. Primary data were obtained by interviewing 109 Nike fishers in Gorontalo Province, as shown in Fig. 1, and consultations with four experts representing government agencies in the same region. Interviews with fishermen were carried out using closed questionnaires. The questionnaire for fisher respondents and experts refers to the attributes in each sustainability dimension modified from Pitcher (1999). Secondary data were obtained from various publications, reports, and other relevant documents that support the objectives of the study.

Data analysis

Data analysis was conducted according to the sustainability evaluation method using RAPFISH software. RAPFISH is an analytical method for evaluating the sustainability of fisheries, which is based on the ordination method focusing on the positioning of elements according to their measurable attributes. This method uses multi-dimensional scaling (MDS), a statistical method to simplify complex multi-dimensional data (Jimenez *et al.,* 2021). MDS in RAPFISH analysis was selected due to the fact that other multi-variate analysis methods, such as factor analysis and multi-attribute utility theory (MAUT), have proven incapable of producing stable results (Pitcher and Preikshot, 2001). In MDS, the object being observed is mapped into two or three-dimensional space so that the object or point is as close as possible to the origin. The configuration or ordination of an object or point in MDS is then approximated by regressing the *Euclidian* distance from point *i* to point *j* (d_{ij}) with the origin (δ_{ij}) using Eq. 1 (Borg *et al.,* 2018).

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (1)$$

The technique used to regress Eq. 1 is the least squares method, which is based on the root of the Euclidian distance (squared distance), called ALSCAL. The ALSCAL algorithm is the most suitable method for RAPFISH and is easily available in almost all statistical software (Alder *et al.,* 2000). The ALSCAL algorithm is used in process regression to iterate until the intercept value in the equation reaches zero (a=0). Therefore, Eq. 1 changes to Eq. 2 (Borg *et al.,* 2018).

$$d_{12} = bD_{12} + e \quad (2)$$

When a stress value of (S) < 0.25 is reached, the repetition process is stopped, and the S value is achieved using Eq. 3 (Borg *et al.,* 2018).

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i \sum_j \left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i \sum_j o_{ijk}^4}\right]} \quad (3)$$

In this study, the sustainability status of Nike fish in Gorontalo Province was evaluated across five main dimensions: ecological, economic, social, technological, and ethical. The framework used to determine these dimensions and their respective attributes was based on the concepts developed by Pitcher and Preikshot (Pitcher, 1999; Pitcher and Preikshot, 2001). The assessment of the sustainability of Nike fish comprised 44 attributes distributed across these dimensions. Specifically, there are eight attributes in the ecological dimension and nine each in the economic, social, technological, and ethical aspects, as shown in Table 1. To identify which attributes have the most significant impact on the sustainability within each dimension, leverage or sensitivity analysis was performed. This analysis is based on the priority order of changes in root mean square (RMS) ordination on the x-axis. When the RMS has a large enough value, this feature's function in determining sustainability becomes more prominent (more sensitive) (Widjaja *et al.,* 2024). Monte Carlo analysis was used to determine the effect of calculation errors and potential misjudgment of attributes by respondents. The smaller the difference between the sustainability index and the Monte Carlo simulation, the more accurate the results (Kavanagh and Pitcher, 2004).

The goodness of Fit in terms of the MDS calculations was indicated by the magnitude of the stress (S) value (Pitcher and Preikshot, 2001). The validity of the model was determined by the magnitude of the coefficient of determination (R^2) (Samimi *et al.,* 2023). A well-fitted model is indicated by an S value of less than 0.25 (< 0.25) and an R^2 of approximately 1. The assessment score for each aspect ranges from 0 (representing the worst or bad scale) to 100 (representing the best or good scale). An index value of more than 50 (> 50) indicates that the aspect being assessed is properly maintained. Conversely, when the index value is < 50, the aspect is unsustainable (Kavanagh and Pitcher, 2004). The categorization of this index is also in accordance with the sustainability index categories, according to Sutaman et al. (2017) and Widjaja et al. (2024). The sustainability index categories according to several references are shown in Table 2.

RESULTS AND DISCUSSION

The sustainability status of Nike fish in several locations within Tomini Bay, including the Gorontalo City Bay, Bone Bolango, Taludaa, Tombulilato, and Bilato estuaries, was analyzed using RAPFISH and ordination analysis supported by the results of Monte Carlo analysis. The results of the ordination and Monte Carlo analyses showed that of the five dimensions assessed, four of them, namely ecological, economic, social, and ethical, had scores less than 50. This implied that these dimensions are in the less sustainable category. The technology dimension had a score greater than 50 and was within the sustainable category. This result is not in line with the initial research expectations, which estimated that all dimensions were less sustainable. The results of the MDS analysis and the sustainability status of Nike fish usage are shown in Table 3.

The results of the RAPFISH analysis are accurate, as proven by the S value and the R^2 shown in Table 3. A decreased S value showed a high degree of accuracy, which reflected a good fit, while the opposite was true in the case of an increased S value (Martias *et al.,* 2023). The results of a good RAPFISH analysis tend to be characterized by an S value of < 0.25 and an R^2 that is approximately 1 (Patawari *et al.,* 2023). The results of the analysis for each sustainability dimension are reported as follows.

Table 1: RAPFISH dimensions and attributes in Nike fish sustainability assessment

Dimension	Attributes
Ecological	Use rate of fish resources
	Total catch
	By-catch
	Nike diversity
	Location of fishing grounds
	Conservation area
	Closed season
	Environmental quality
Economic	Economic value
	Marketing distribution
	Source of livelihood
	Subsidy dependency
	Contribution to regional revenue
	Profit distribution
	Labor absorption
	Business prospects
	Income relative to provincial minimum wage
Social	Education level
	Environmental knowledge
	Level of conflict
	Development of fishermen
	Community role in sustainability
	Fishermen role in sustainability
	Participation of family members
	Level of business socialization
	Fishermen role in planning
Technological	Tool selectivity
	Shipboard handling
	Ship size
	Tool use
	Negative effect on habitat
	Safety for fishermen
	Threat to protected fish
	Fish landing sites
	Post-harvest handling
Ethical	Rules and regulations
	Level of violation
	Mitigation of ecosystem damage
	Habitat damage mitigation
	Waste discharges (externalities)
	Customary rules and local wisdom
	Fishermen role in policy
	Access to resources
	Alternative employment

Table 2: Index values and sustainability categories

Sustainability categories	Index value		
	Kavanagh and Pitcher, 2004	Sutaman *et al.*, 2017	Widjaja *et al.*, 2024
Bad: unsustainable	0-24.99	0-25	0-25
Less: less sustainable	25-49.99	26-50	25.01-50
Sufficient: quite sustainable	50-74.99	51-75	50.01-75
Good: very sustainable	75-100	76-100	75.01-100

Table 3: Results of RAPFISH analysis on the sustainability status of Nike fish use

Dimension	Average MDS score across five study sites	S	R^2	Sustainability Index Category	Average Monte Carlo Values across five study sites	Difference between MDS and Monte Carlo
Ecological	33.53	0.14	0.94	Less: less sustainable	34.78	1.25
Economic	40.33	0.15	0.93	Less: less sustainable	40.78	0.45
Social	30.86	0.14	0.94	Less: less sustainable	31.19	0.33
Technological	84.09	0.14	0.94	Good: very sustainable	81.65	2.44
Ethical	25.19	0.14	0.91	Less: less sustainable	26.04	0.85

Ecological dimension

In the ecological dimension, eight attributes were assessed, including the use level of fish resources, the size of the catch, fish species diversity, by-catch, the locations of fishing and conservation areas, closed season, and environmental quality. The ordination analysis showed a sustainability index of 33.53 for Nike fish use in the less sustainable category. To evaluate the potential impact of errors related to scoring and the ordination process on determining the sustainability status, the results of the Monte Carlo analysis were examined. Monte Carlo analysis is a simulation method used to evaluate the effect of random errors on all dimensions (Saputro *et al.,* 2023). Preserving the sustainability of the ecological dimension in capture fisheries is a critical concern. It is essential to prevent the over-exploitation of fish resources in a given water body, ensuring they remain within their availability and carrying capacity (Fu *et al.,* 2018). The main concern in the concept of ecologically sustainable fisheries development focuses on the maintenance of stock or biomass sustainability, as well as increasing the capacity of the ecosystems without exceeding their carrying capacity (Zhang *et al.,* 2022). Detailed results from the ordination and Monte Carlo analyses and the leverage analysis are shown in Fig. 2.

The highest attribute values identified in the leverage analysis showed the attributes that require special attention in supporting the sustainability of Nike fish use. The three attributes that need to be considered in supporting the sustainable use of Nike fish in the ecological dimension are shown in Fig. 2a-b. These include the location of the fishing area, species diversity, and by-catch. The location of Nike fishing in Tomini Bay, Gorontalo Province, remains the same (fixed) due to its unique amphidromous nature. Their eggs are carried by the river currents and hatch in estuary areas, leading to a stable fishing location. This finding is similar to Castellanos-Galindo (2011), who states that relatively permanent fishing locations were also found in the Pacific Ocean, North Colombia. Fishing locations are an important issue in fisheries, especially artisanal fisheries. Fishermen in artisanal fisheries tend to use simple and cheap fishing gear, and most fishing locations are close to the beach/shallow areas (Batista *et al.,* 2014). These findings indicate the need to protect fishing locations by conserving the habitat and areas of amphidromous fish (Franklin *et al.,* 2019). Species diversity is also a highly sensitive attribute, and the results obtained showed that the types of fish caught at the five fishing locations varied from 11 to 12 species (Sahami *et al.,* 2022). Maintaining this diversity is critical to prevent the extinction of Nike fish. Species extinction can be one of the main factors resulting in a biodiversity crisis (Modesto *et al.,* 2018). Resource conservation is an effort that can be made to help ecological systems support a higher diversity of species (Silva *et al.,* 2015). Fishing intensity and quantity caught by fishermen each season are quite high, posing a potential threat to the sustainability of Nike fish (Pasisingi and Olii, 2023). The Indonesian community has long engaged in consumptive and ornamental uses of the fish. The conservation aspect needs to be considered for its sustainability (Niesenbaum, 2019). Based on interview results and direct observations during fishing activities, the by-catch in terms of Nike fishing is very small (<10 percent: %). This small by-catch should be preserved to avoid disrupting the food chain of the aquatic community. Global regulations, such as the Food and Agriculture Organization (FAO) Code of Conduct on Responsible Fisheries, require fishermen to reduce the amount of by-catch to lessen

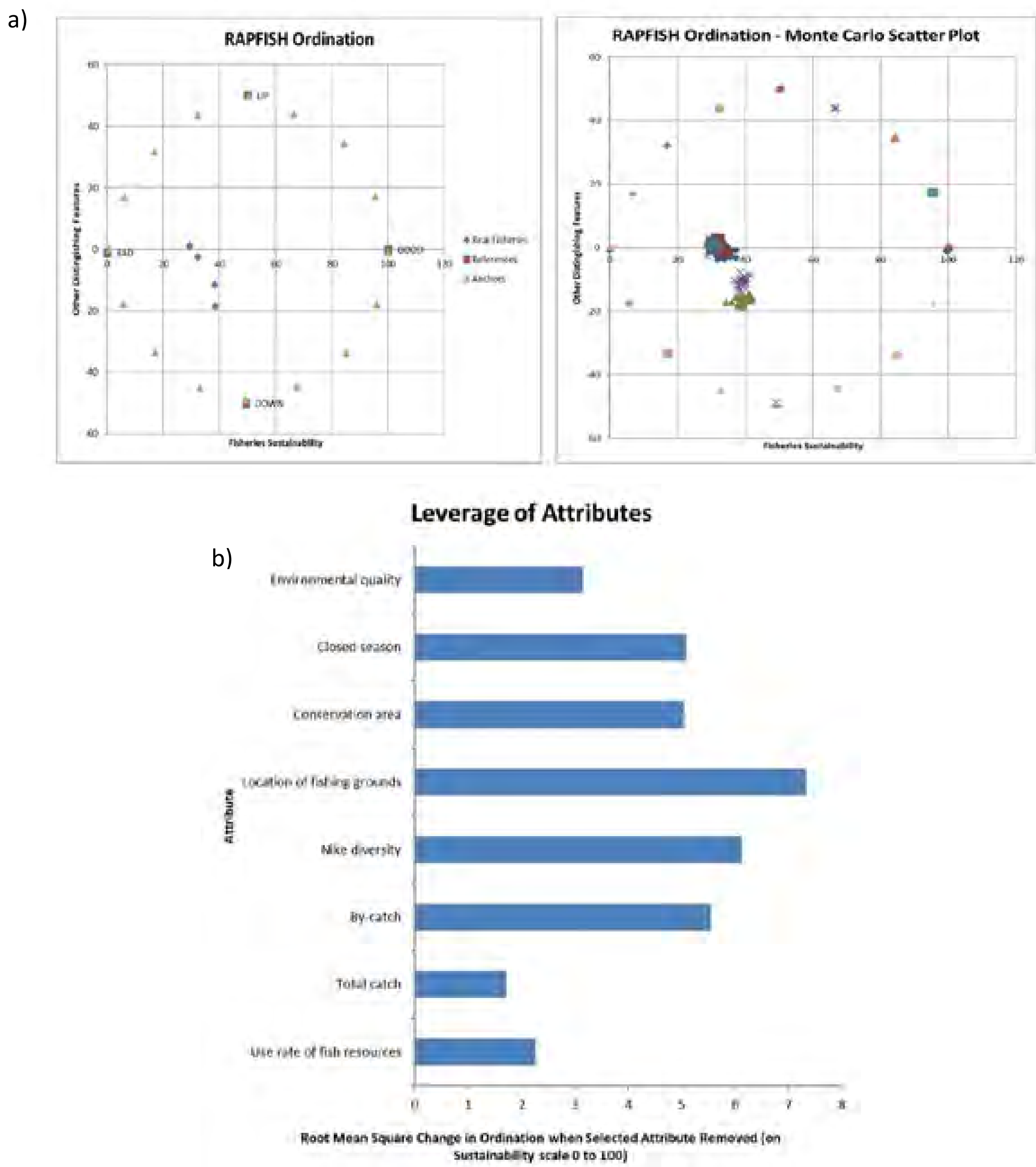

Fig. 2: (a): Results of ordination and Monte Carlo analysis; (b): leverage of attributes on the ecological dimension

the environmental impact of their fishing methods. These regulations ensure that all countries adhere to the fundamental principles of sustainable fisheries management.

Economic dimension

This study evaluates the economic dimension using a range of attributes, including attributes used to analyze the economic dimension in the existing study, such as 1) the economic value (profit), 2) marketing distribution, 3) source of livelihood, 4) subsidy dependency, 5) contribution to regional revenue, 6) profit distribution, 7) employment, 8) business prospects, and 9) income relative to the provincial minimum wage. The ordination and Monte Carlo analyses showed that the sustainability index value for the economic dimension of Nike fishing in Tomini Bay, Gorontalo Province, was 40.33, as shown in Table 3. Based on the classification of the sustainability status, this figure falls within the less sustainable category. The results of the leverage analysis identified three attributes that significantly impact the economic dimension sustainability index, as shown in Fig. 3a-b.

These attributes include profit distribution,

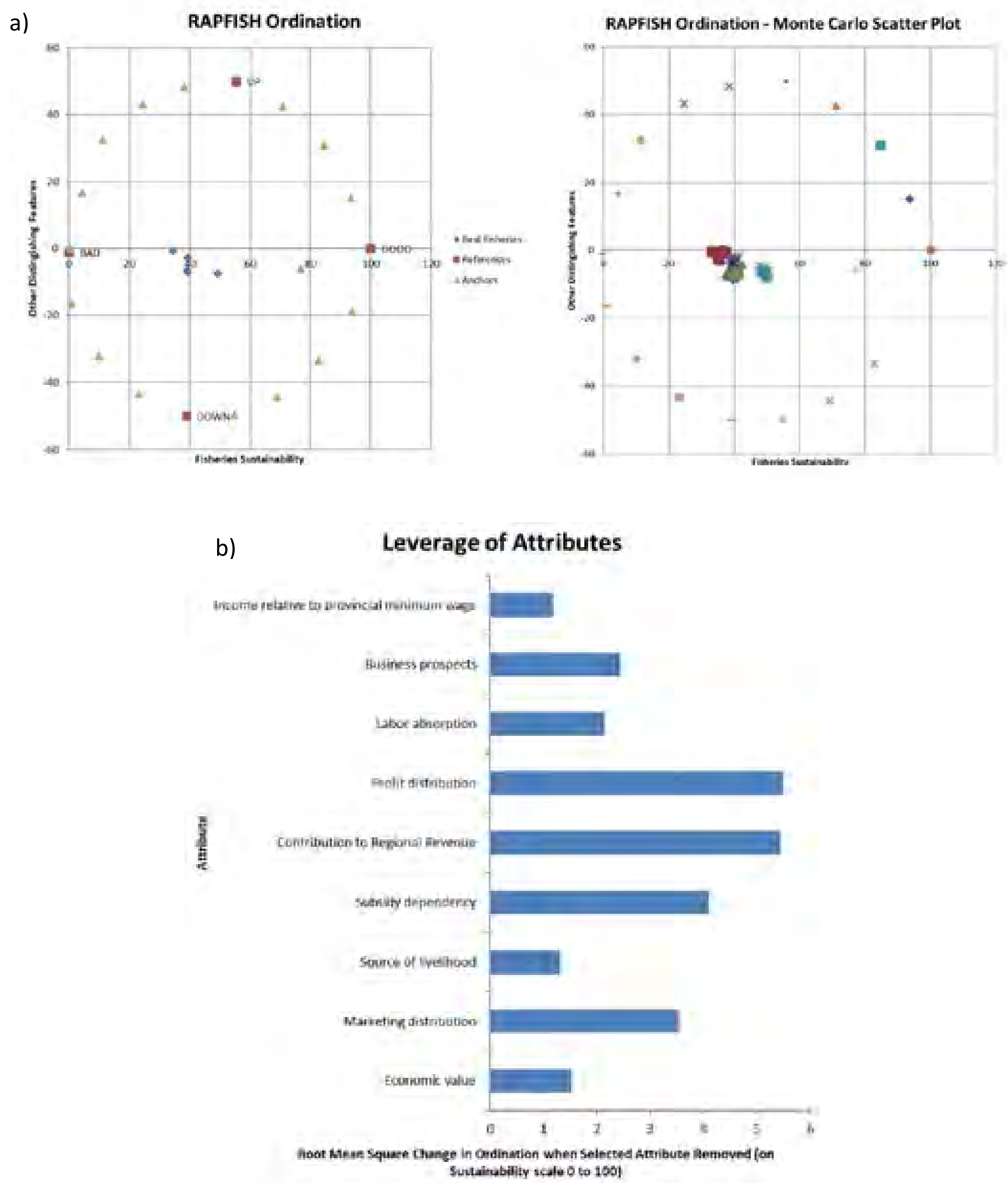

Fig. 3: (a) Results of ordination and Monte Carlo analysis; (b): leverage of attributes on the economic dimension.

contribution to regional revenue, and subsidy dependence. Profit distribution is one of the attributes that have the highest sensitivity in the economic dimension. Interviews with Nike fishermen showed that Nike fishing activities are generally conducted in groups, where capital owners achieve greater profit distribution. As part of this practice, the profits obtained are distributed among group members after deducting business capital, maintenance costs, and expenses incurred from repairing damaged fishing gear. The profit distribution in this study is similar to Hendrik *et al.* (2020), which mentions the wage and profit sharing system at the Belawan Ocean Fishing Port, North Sumatra Province, where the owner or investor has a 60% share and working fishermen have a 40% share of the profits from the catch. This profit-sharing system does not follow Indonesian Fishing Regulation No. 16/1964 due to the lower wages provided to working fishermen. According to Benner and Wrubel (1989), the pattern of cooperation between fishermen who own capital and fishermen who work in the local areas is complicated and will be difficult to change. The profit-sharing system implemented tends to benefit fishermen who own capital. This system has an impact on the low investment development of fishermen and the weak economic, social, and political position of fishermen, which ultimately has an impact on their economic welfare (Fauzi and Anna, 2005). The unequal distribution of profits can lead to the overexploitation of resources (Tietenberg and Lewis, 2012) and has the potential to give rise to other problems such as poverty and crime. To achieve economic sustainability, efforts to improve profit distribution should refer to Indonesian Fishing Regulation No. 16/1964. The next attribute that affects the sustainable use of Nike fish in the economic dimension is the contribution to regional revenue. Information obtained from stakeholder interviews showed that the contribution of regional revenue use activities in Gorontalo Province is minimal. This is because most catches are not sold through fish auction sites but directly to collectors, except for fishermen in Gorontalo City. The most substantial sources of regional revenue come from local levies obtained through tax levies on auction sites and markets (Syamsuddin, 2021). The irregular and seasonal occurrence of Nike fish is a major reason for the absence of revenue collection from this source. Dependence on subsidies is another contributing factor, especially the fuel oil subsidy provided by the government to support the fisheries sector. This subsidy has been prohibited since 2020, as stated in the Sustainable Development Goals (SDGs) item 14. Dependence on subsidies can have both positive and negative effects. On the positive side, it can stimulate the development of fisheries, increasing national income, while the negative aspects are related to destructive practices, such as illegal, unreported, unregulated fishing (IUUF).

Social dimension

The ordination and Monte Carlo analyses (Fig. 4a) showed that the sustainability index value for the social dimension of Nike fishing in Tomini Bay, Gorontalo Province, is 30.86. This places it within the less sustainable category. The social dimension of the sustainability status of Nike fishing includes the analyses of nine attributes to determine the main sensitivities. The leverage analysis identified two attributes as the most sensitive in influencing the sustainability of the social dimension. These include the level of conflict and the fishermen role in sustainability, as shown in Fig. 4b. The level of conflict is the most influential attribute that affects the sustainability of Nike fish use in Gorontalo Province. Conflict between fishermen tends to occur due to scarce resources, structural imbalances within the group, misinformation, competitive desires, and poor peer relationships (Devlin *et al.,* 2022). Based on interviews held with Nike fishermen in Gorontalo Province, no conflict has been reported, thereby indicating a positive practice that needs to be maintained. This harmony is attributed to their adherence to local wisdom, a fundamental part of the Gorontalo community culture. Local wisdom, including concepts like *huyula*, *heeluma*, and *hiimbunga* (local name), instills a habit of tolerance and family-oriented conflict resolution (Yunus, 2014). The next attribute that affects sustainability in the social dimension is the fishermen role in sustainability. The results of the interviews showed that Nike fishers tend to pay less attention to the long-term sustainability of this species, often engaging in large-scale catches when fish is abundant. This continuous fishing practice during each season tends to threaten the future sustainability of Nike fish. The decline in Nike fish production from 2020 (average 7.95 tons/month) to 2021 (2.04 tons/month) indicates a

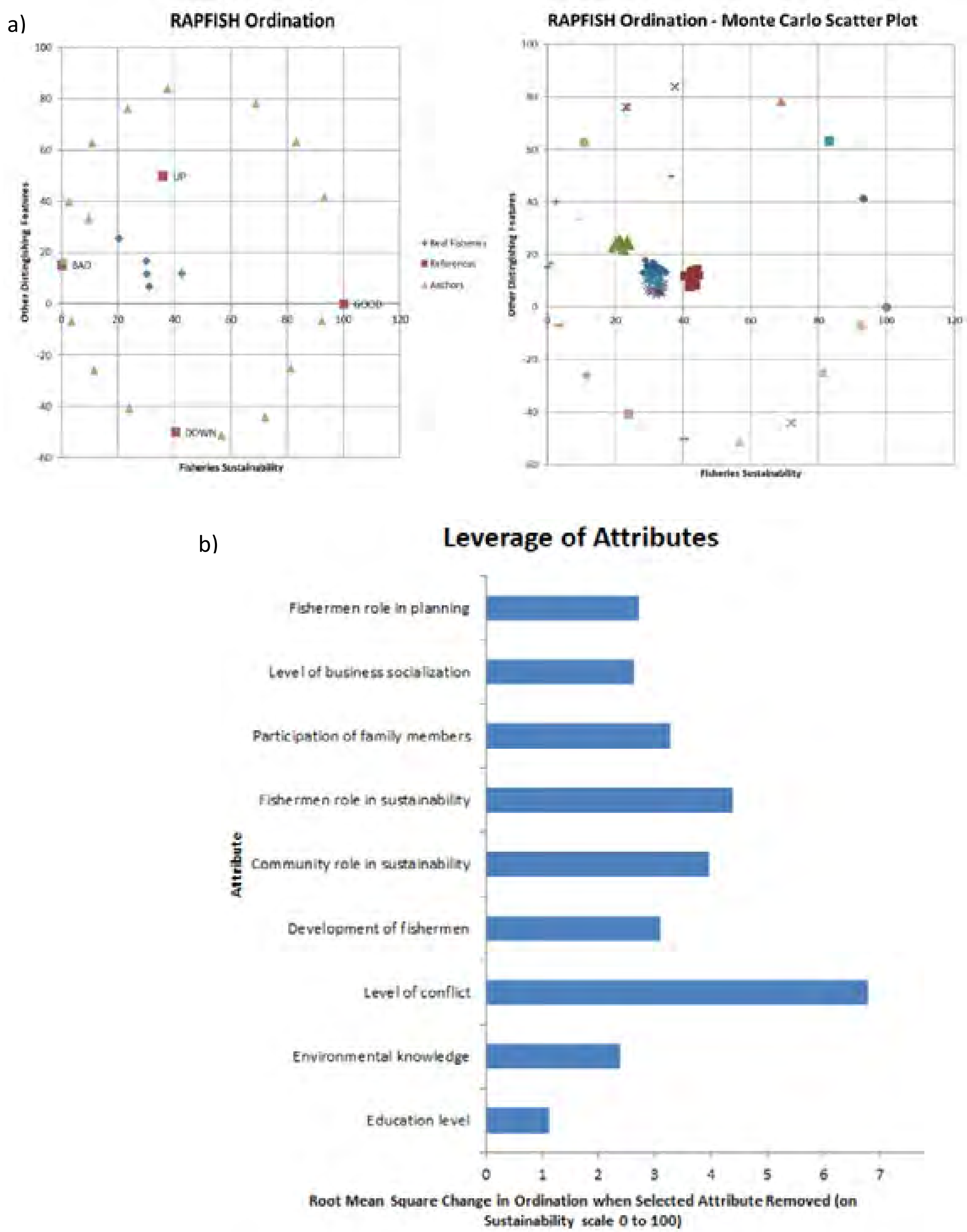

Fig. 4: (a) Results of ordination and Monte Carlo analysis; (b): leverage of attributes on the social dimension.

threat to the sustainability of these fish resources. The role of fishermen in conservation efforts plays an important strategy in resource sustainability (Neubauer *et al.,* 2013). It is essential to conduct awareness campaigns through socialization and establish community watchdog groups to preserve Nike fish resources. Fisher and fishing communities must learn fishing practices that support resource sustainability (Nunoo *et al.,* 2015). Involving local community knowledge can also increase the success of resource management and conservation (Adiga *et al.,* 2015). Local community knowledge can also contribute to determining fisheries management monitoring measures (Dias *et al.,* 2020).

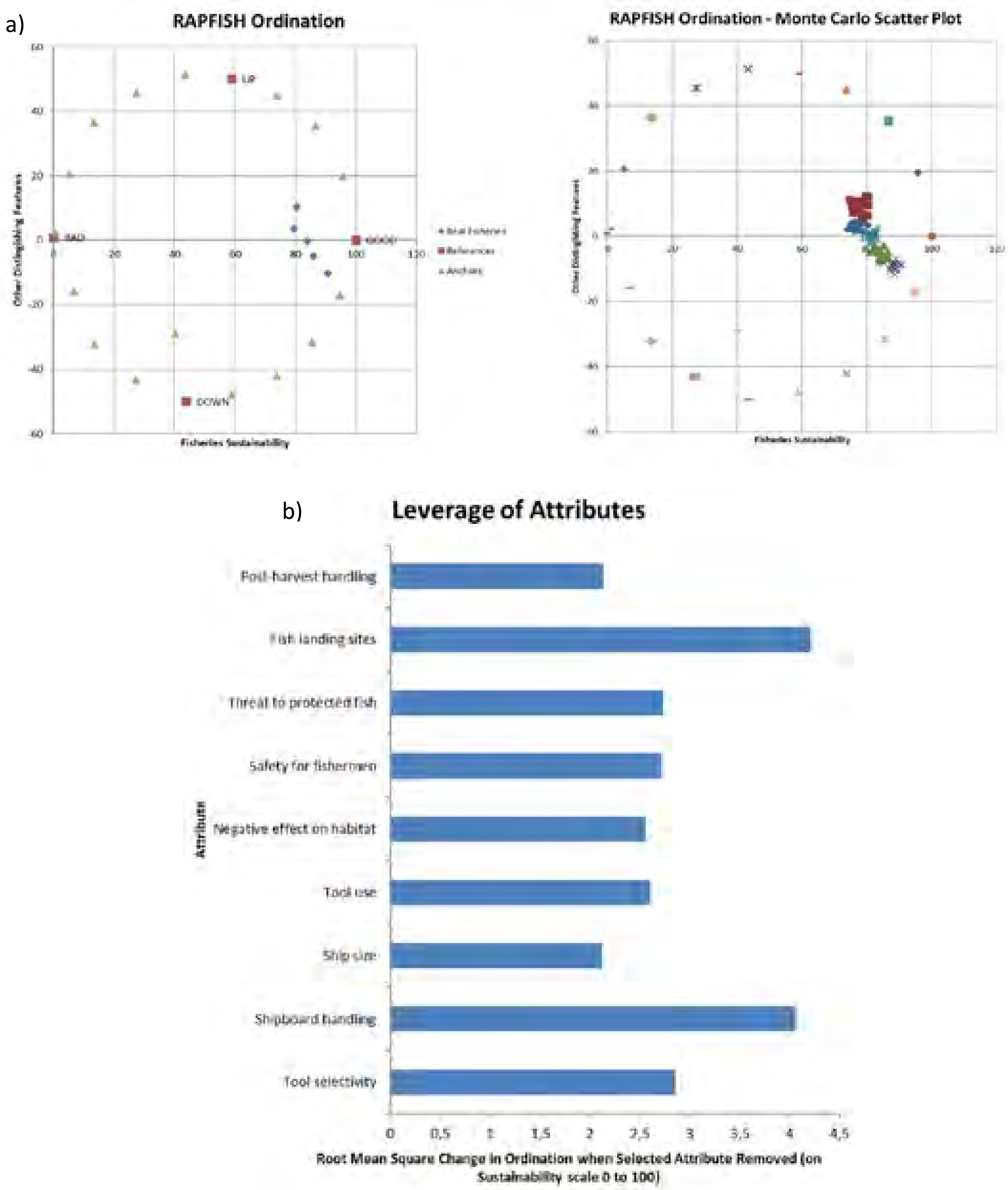

Fig. 5: (a) Results of ordination and Monte Carlo analysis; (b): leverage of attributes on the technology dimension.

Technology dimension

The technological dimension is a significant factor in assessing the sustainability of Nike fishing. The ordination and Monte Carlo analyses results showed a sustainability value of 84.09, and when viewed through the technological dimension, the Nike fish in the waters of Tomini Bay were within the sustainable category. Technology is the only dimension that has a sustainable status in this study. The distribution of ordination values at each Nike fishing location further supported the sustainability status of the technological dimension, as shown in Fig. 5a. Nine attributes were used to analyze the sustainability of the technological dimension, namely fishing gear selectivity, onboard handling, vessel size, use of auxiliary tools, negative effect on habitat, fisher safety, threatening protected fish, fish landing site, and post-harvest handling, as shown in Fig. 5b. The results of the leverage analysis showed that two attributes, fish landing sites and onboard handling, have a significant impact on the sustainability index of the technology dimension. The interviews with Nike fishing fishermen showed mixed results for each Nike fishing location. At the Taludaa Estuarine fishing site, it was found that landing sites for Nike fish were properly distributed with adequate facilities. For the Tombulilato, Bilato, and Bone-Bolango estuaries, fish landing sites were concentrated in one location. For the Bilungala estuary, the Nike fish landing site was reported to be inadequate. To ensure the sustainable use of this species, special attention and various policies need to be implemented to address this attribute. The existence of a port greatly influences the success of the fishing industry as a landing place for fish catches (Huntington *et al.,* 2015). The proper management of fish landing ports is essential to support the quality and sustainability of fisheries businesses (Lubis and Pane, 2017).

Ethical dimension

The sustainability index for the ethical dimension of Nike fishing was determined to be 25.19 across the five fishing sites, as shown in Fig. 6a. This score showed that the ethical dimension was considered less sustainable when compared to the others under investigation. The study identified nine specific attributes that impact the sustainability of the ethical dimension, as shown in Fig. 6b. The results of the leverage analysis showed that two critical attributes significantly impact the sustainability index, namely externalities (waste disposal) and the level of violations. In terms of externalities, interviews held with certain practitioners showed that waste resulting from Nike fishing activities is typically minimal or occasionally absent. This was due to traditional boats and simple fishing gear, which support this attribute by reducing waste disposal. Fishermen stated that they generally avoid discarding hazardous materials or waste into the sea. Regarding the level of violations, the interview results showed that minimal violations were committed in the five study sites. The use of traditional boats and simple fishing gear contributed to the minimal level of violation. The seasonal pattern of Nike fish occurrence (Olii *et al.,* 2017) is believed to contribute to the minimal level of violations committed by fishermen.

The study results have shown that, in general, the sustainability of Nike fish in all fishing locations within Tomini Bay, Gorontalo, is threatened. To ensure the future sustainability of this species, it is essential to address the main attributes in each dimension. An important element is the establishment of sustainable livelihoods, which includes the capacity to withstand and recover from pressures and shocks while safeguarding and improving the necessary assets for natural resource use (Mensah and Enu-Kwesi, 2019). Riverine amphidromous gobies on tropical islands exhibit continuous high reproduction in response to environmental uncertainties. Their larvae encounter diverse environmental challenges, including temperature fluctuations and food availability, as they drift from downstream areas to the sea (Teichert *et al.,* 2016). Reproductive activity is mainly influenced by the temperature of the water in upstream areas and is also affected by factors like female body condition and competition in downstream areas (Keith *et al.,* 2015). The sustainability of Nike fish in the future is dependent on the availability of the river, which serves as a critical environment for their growth, reproduction, and the transition of eggs into the sea and juveniles back to the river. Effective management of the adult phase, including the avoidance of overfishing gobies and the release of those carrying eggs when caught, is also important (Sahami and Habibie, 2020). Environmental conditions, as proven by the negative growth pattern of Nike fish and its length–weight relationship (LWR) analysis, play a significant role in the production

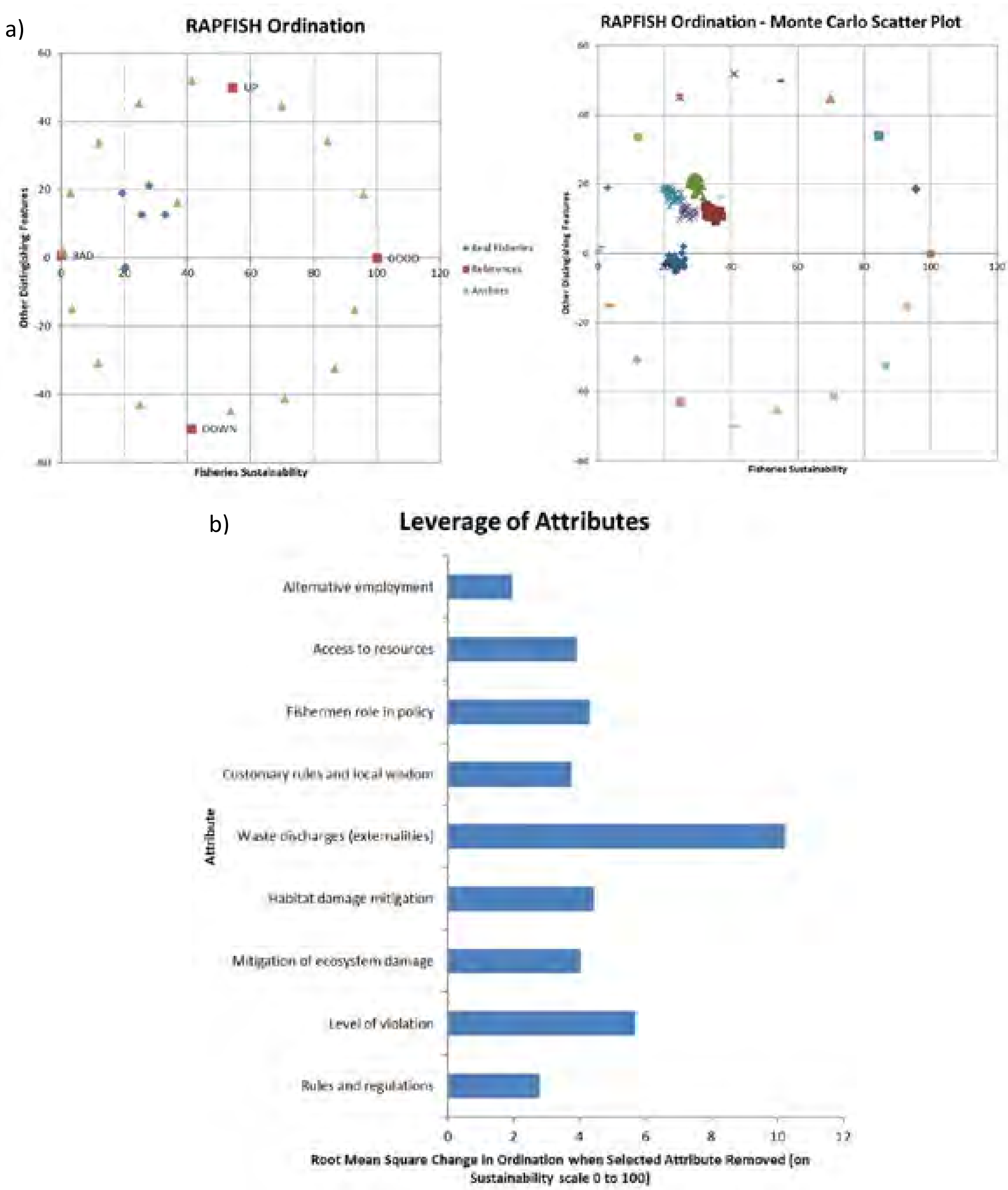

Fig. 6: (a) Results of ordination and Monte Carlo analysis; (b): leverage of attributes on the ethical dimension.

process (Sahami *et al.,* 2023). The sustainability of Nike tends to depend on future actions. To achieve this, it is imperative to combine high fishing efforts with effective habitat management, ensuring long-term sustainability (Sahami and Habibie, 2020). The connection between environmental and livelihood sustainability is extremely important. In essence, the entire framework for sustainable livelihoods is dependent on the concept of ensuring that it is maintained (Mensah and Enu-Kwesi, 2019). Ecosystem management-based methods and models have been proposed in the quest for sustainable fisheries. These methods regulate the management of fisheries resources and contribute to the sustainable development of the economy and society (Bi *et al.,* 2023). The sustainability of seafood production does not depend solely on the abundance of fish stocks. It mainly focuses on the ability of fisheries management systems to adapt fishing pressure to appropriate levels (Hilborn *et al.,* 2015). Two main recommendations that can be given to local governments are: 1) Create regulations regarding the management of Nike fish resources, and 2) increase the knowledge of fishermen and local communities regarding the eco-biology of Nike fish.

CONCLUSION

In conclusion, the novelty of this study was the use of five dimensions, namely ecological, economic, social, technological, and ethical dimensions, to evaluate and assess the sustainability status of amphidromous Nike fish resources in the waters of Tomini Bay, Gorontalo, which includes the Bone-Bolango, Bilungala, Tombulilato, Taludaa, and Bilato estuaries. The sustainability status was assessed using RAPFISH with the MDS approach. A total of forty-four factors that influence sustainability across five dimensions were considered in this study. The MDS analysis found that of the five dimensions examined, only one dimension, the technological dimension, showed sustainable status (>50), with an average index value of 84.09. In contrast, the other four dimensions, namely the ecological, economic, social, and ethical dimensions, showed less sustainable status (<50), with average index values of 33.53, 40.33, 30.86, and 25.19. The S value and the R^2 in the MDS calculation ranged from 0.14 to 0.15 and 0.91 to 0.94, indicating that the analysis is appropriate. The sustainability status of each dimension was found to have the same trend in all research locations. It was reported that the sustainability of using Nike fish resources in Tomini Bay, Gorontalo, was threatened. From the results of the leverage analysis, it was found that twelve leverage attributes were identified as having had a significant effect on the sustainability of Nike fish resources in the waters of Tomini Bay, Gorontalo. The government and stakeholders prioritized the leverage attributes to formulate appropriate management policies to ensure the future sustainability of Nike fish in the waters of Tomini Bay. As the dimension with the lowest average index value, the primary focus must be on the ethical dimension in order to increase the sustainability of the use of Nike fish resources, emphasizing 1) externalities (waste disposal) and 2) the level of violations. The next dimension that needs to be prioritized is the social dimension, with particular emphasis related to 1) the level of conflict and 2) the role of fishermen in sustainability. Leverage attributes such as 1) the location of fishing grounds, 2) Nike diversity, and 3) by-catch need to be prioritized concerning the ecological dimension. Minimal externalities (waste disposal), low level of violations, minimal conflict, and minimal by-catch from research findings do not guarantee sustainability in the ethical and social dimensions, as proven by the low value of the sustainability index in the ethical and social dimensions. Further, in the economic dimension, factors such as 1) profit distribution, 2) contribution to regional revenue, and 3) dependence on subsidies were identified as important to achieve sustainable implementation. For the technological dimension as the only dimension that indicates sustainable status, factors such as 1) fish landing sites and 2) handling on board need to be improved. This study provides a valuable contribution to the government as a reference for policymaking in developing strategies for the sustainable use of these species in the waters of Tomini Bay, Gorontalo. Even though this study focuses on the waters of Tomini Bay, Gorontalo, the results can provide information or insight for countries with similar fisheries potential to carry out better management.

AUTHOR CONTRIBUTIONS

F.M. Sahami, the corresponding author, was responsible for all study activities, from conception and design, drafting, and critical revision of the manuscript. S.N. Hamzah contributed to conception and design, analyzing and interpreting the data, and preparing the manuscript. A.H. Tome collected the data and critical revision of the manuscript. S.A. Habibie collected and acquisition of data, statistical analysis, and drafting the manuscript. M.R.U. Puluhulawa analyzed and interpreted data.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely witnessed by the authors.

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ABBREVIATIONS

%	Percent
<	Less than
>	More than
ALSCAL	The root of the Euclidian distance
cm	Centimeter
COI	Cytochrome oxidase subunit I
d_{ij}	Euclidian distance from point i to point j
DNA	deoxyribonucleic acid
E	East
et al.	Et alia
FAO	Food and Agriculture Organization
Fig.	Figure
IUUF	Illegal, unreported, unregulated fishing
LWR	Length-weight relationship
MAUT	Multi-attribute utility theory
MDS	Multi-dimensional scaling
N	North
R^2	Coefficient of determination
RAPFISH	Rapid appraisal for fisheries
RMS	Root mean square
S	Stress
SDGs	Sustainable development goals
x-axis	Horizontal number line

REFERENCES

Adiga, M.S.; Ananthan, P.S.; Ramasubramanian, V.; Kumari, H.V.D., (2015). Validating RAPFISH sustainability indicators: focus on multi-disciplinary aspects of Indian marine fisheries. Mar. Policy. 60: 202-207 **(6 pages).**

Alder J.; Pitcher, T.J.; Preikshot, D.; Kaschner, K.; Feriss, B., (2000). How good is good? A rapid appraisal technique for evaluation of the sustainability status of fisheries of the North Atlantic. Sea Around Us Methodol. Rev., 8(2): 136–182 **(47 pages).**

Alder, J.; Zeller, D.; Pitcher, T.; Sumaila, R., (2002). A method for evaluating marine protected area management. Coast Manage., 30(2): 121-131 **(11 pages).**

Batista, V.S.; Fabré, N.N.; Malhado, A.C.M.; Ladle, R.J., (2014). Tropical artisanal coastal fisheries: challenges and future directions. Rev. Fish. Sci. Aquac., 22(1): 1-15 **(15 pages).**

Benner, P. E.; Wrubel, J., (1989). The primary of caring stress and coping in health and illness. The Addison Wesley Pub. Co., California.

Bi, M.; Zhang, Z.; Guo, X.; Wan, L., (2023). Evaluation of Sustainable Utilization of African Marine Fishery Resources. Fishes. 8(1): 4.

Borg, I.; Groenen, P.J.F.; Mair, P., (2018). Applied Multidimensional Scaling and Unfolding. Springer.

Castellanos-Galindo, G.A.; Sanchez, G.C.; Beltrán-León, B.S.; Zapata L., (2011). A goby-fry fishery in the northern Colombian Pacific Ocean. Cybium. 35: 391–395 **(5 pages).**

Devlin, C.; Glaser, S.M.; Lambert, J.E.; Villegas, C., (2022). The causes and consequences of fisheries conflict around the Horn of Africa. J. Peace Res., 59(6): 890-902 **(13 pages).**

Dias, A.C.E,; Cinti, A.; Parma, A.M.; Seixas, C.S., (2020). Participatory monitoring of small-scale coastal fisheries in South America: use of fishers' knowledge and factors affecting participation. Rev. Fish Biol. Fish. 30: 313-333 **(21 pages).**

Fauzi, A.; Anna, S., (2005). Pemodelan Sumber Daya Perikanan dan Kelautan untuk Analisis Kebijakan. PT Gramedia Pustaka Utama. Jakarta.

Franklin, P; Gee, E., (2019). Living in an amphidromous world: Perspectives on the management ff ish passage from an island nation. Aquatic Conserv: Mar Freshw Ecosyst., 29: 1424–1437 **(14 pages).**

Fu, X.M.; Zhang, M.Q.; Liu, Y.; Shao, C.L.; Hu, Y.; Wang, X.Y.; Su, L.R.; Wang, N.; Wang, C.Y., (2018). Protective exploitation of marine bioresources in China. Ocean Coast. Manage., 163: 192-204 **(13 pages).**

Hein, C.L; Crowl, T.A., (2010). Running the predator gauntlet: do freshwater shrimp (Atya lanipes) migrate above waterfalls to avoid fish predation?. J. North Am. Benthol. Soc., 29(2): 431–443 **(14 pages).**

Hendrik, H.; Hamid, H.; Alvionita, D.; Alfrendo, A., (2020). Wage system and profit sharing in fish catching business using lift net in Ocean Fishing Port of Belawan. IOP Conference Series: Earth Environ. Sci., 430: 012017 (**7 pages**).

Hilborn, R.; Fulton, E.A.; Green, B.S.; Hartmann, K.; Tracey, S.R.; Watson, R.A., (2015). When is a fishery sustainable?. Can. J. Fish Aquat. Sci., 72(9): 1433-1441 **(9 pages).**

Huntington, T.; Nimmo, F.; Macfadyen, G., (2015) Fish landings at the world's commercial fishing ports. J. Ocean Coastal Econ., 2(1): 1-9 **(9 pages).**

Iida, M.; Kondo, M.; Tabouret, H.; Maeda, K.; Pécheyran, C.; Hagiwara, A.; Keith, P.; Tachihara, K., (2017). Specific gravity and migratory patterns of amphidromous gobioid fish from Okinawa Island, Japan. J. Exp. Mar. Biol. Ecol., 486: 160-169 **(10 pages).**

Jackson, J.M.; Lenz, P.H., (2016). Predator–prey interactions in the plankton: larval fish feeding on evasive copepods. Sci. Rep., 6: 1-11 **(11 pages).**

Jenkins, A.P.; Jupiter, S.D.; Qauqau, I.; Atherton, J., (2010). The importance of ecosystem-based management for conserving aquatic migratory pathways on tropical high islands: a case study from Fiji. Aquatic Conserv: Mar. Freshw. Ecosyst., 20: 224-238 **(15 pages).**

Jimenez, É.A.; Gonzalez, J.G.; Amaral, M.T.; Frédou, F.L., (2021). Sustainability indicators for the integrated assessment of coastal small-scale fisheries in the Brazilian Amazon. Ecol. Econ., 181: 1-14 **(14 pages).**

Kavanagh, P.; Pitcher, T.J., (2004). Implementing Microsoft Excel Software for Rapfish: A Technique for the Rapid Appraisal of Fisheries Status. Fisheries Centre, University of British Columbia, Canada.

Keith, P.; Lord, C., (2011). Tropical freshwater gobies: amphidromy as a life cycle, in: Patzner, R.A., Van Tasell, J.L., Kovacic, M., Kapoor, B.G. (Eds), The Biology of Gobies. Science Publishers Inc., New York.

Keith, P.; Lord, C.; Busson, F.; Sauri, S.; Hubert, N.; Hadiaty, R.K., (2015). A new species of *Sicyopterus* (Gobiidae) from Indonesia. Cybium. 39(4): 243-248 **(6 pages).**

Lubis E.; Pane A.B., (2017) Institutional model of fish auction refunctionalization in Indonesian fishing ports. AACL Bioflux. 10(6): 1456-1465 **(10 pages).**

Maie, T.; Wilson, M.P.; Schoenfuss, H.L.; Blob, R.W., (2009). Feeding kinematics and performance of Hawaiian stream Gobies, *Awaous guamensis* and *Lentipes concolor*: linkage of functional morphology. J. Morpho., 270(3): 344-356 **(13 pages).**

Marina, B.; Svetlana, K.; Francesco, F., (2021). The long-term ichthyoplankton abundance summer trends in the coastal waters of the Black Sea under conditions of hydrometeorological changes. Estuar. Coast. Shelf Sci., 258: 1-7 **(7 pages).**

Martias, I.; Rifardi, R.; Agrina, A.; Suprayogi, I., (2023). Sustainable healthy settlement on a small island as a cultural heritage area. Global J. Environ. Sci. Manage., 9(SI): 107-126 **(20 pages).**

Mensah, J.; Enu-Kwesi, F., (2019). Implications of environmental sanitation management for sustainable livelihoods in the catchment area of Benya Lagoon in Ghana. J. Integr. Environ. Sci., 16(1): 23-43 **(21 pages).**

Modesto, V.; Ilarri, M.; Souza, A.T.; Lopes-Lima, M.; Douda, K.; Clavero, M.; Sousa, R., (2018). Fish and mussels: importance of fish for freshwater mussel conservation. Fish Fish., 19(2): 244-259 **(16 pages).**

Neubauer, P.; Jensen, O.P.; Hutchings, J.A.; Baum, J.K., (2013). Resilience and recovery of overexploited marine populations. Science. 340 (6130): 347-349 **(3 pages).**

Niesenbaum, R.A., (2019) The Integration of conservation, biodiversity, and sustainability. Sustainability. 11(17): 1-11 **(11 pages).**

Nunoo, F.K.E.; Asiedu, B.; Olauson, J.; Intsiful, G., (2015). Achieving sustainable fisheries management: a critical look at traditional fisheries management in the marine artisanal fisheries of Ghana, West Africa. J. Energy Nat. Resour. Manage., 2(1): 1-9 **(9 pages).**

Olii, A.H.; Sahami, F.M.; Hamzah, S.N.; Pasisingi, N., (2017).

Preliminary findings on distribution pattern of larvae of nike fish (*Awaous* sp.) in the estuary of Bone River, Gorontalo Province, Indonesia. AACL Bioflux. 10(5): 1110-1118 **(19 pages).**

Pasisingi, N.; Olii, A.H., (2023). Fishermen and nike fishing in Gorontalo Bay, Gulf of Tomini (Indonesia). Jurnal Sumberdaya Akuatik Indopasifik. 7(3): 239-252 **(14 pages).**

Patawari, A.M.Y.; Anna, Z.; Hindayani, P.; Dhahiyat, Y.; Hasan, Z.; Putri, I.A.P., (2023). Sustainability status of small-scale fisheries resources in Jakart Bay, Indonesia after reclamation. AACL Bioflux. 23(4): 1715-1725 **(11 pages).**

Pitcher, T.J., (1999). Rapfish, A Rapid Appraisal Technique for Fisheries, and Its Application to the Code of Conduct for Responsible Fisheries. FAO Fisheries Circular, Rome.

Pitcher, T.J.; Preikshot, D., (2001). Rapfish: a rapid appraisal technique to evaluate the sustainability status of fisheries. Fish. Res., 49(3): 255-270 **(16 pages).**

Roman, M.R.; Brandt, S.B.; Houde, E.D.; Pierson, J.J., (2019). Interactive effects of hypoxia and temperature on coastal pelagic zooplankton and fish. Front. Mar. Sci., 6: 1-18 **(18 pages).**

Sahami, F.M.; Habibie, S.A., (2020). Exploration of adult phase of nike fish to maintain its sustainability in Gorontalo Bay waters, Indonesia. AACL Bioflux. 13(5): 2859-2867 **(9 pages).**

Sahami, F.M.; Habibie, S.A., (2021). Diversity of species in making up Nike fish schools and a new record of *Eleotris melanosoma* in Tomini Paguyaman Bay, Gorontalo, Indonesia. Biodiversitas. 22(12): 5459-5467 **(9 pages).**

Sahami, F.M.; Kepel, R.C.; Olii, A.H.; Pratasik, S.B., (2019a). Determination of morphological alteration based on molecular analysis and melanophore pattern of the migrating Nike fish in Gorontalo Bay, Indonesia. AACL Bioflux. 12(4): 1358-1365 **(8 pages).**

Sahami, F.M.; Kepel, R.C.; Olii, A.H.; Pratasik, S.B., (2019b). What species make up the Nike fish assemblages at the macrotidal estuary in Gorontalo Bay, Indonesia?. F1000 Res., 8(1654): 1-6 **(6 pages).**

Sahami, F.M.; Kepel, R.C.; Olii, A.H.; Pratasik, S.B.; Lasabuda, R.; Wantasen, A.; Habibie, S.A., (2020). Morphometric and genetic variations of species composers of nike fish assemblages in gorontalo bay waters, Indonesia. Biodiversitas. 21(10): 4571–4581 **(11 pages).**

Sahami, F.M.; Hamzah, S.N.; Habibie, S.A., (2023). Length-weight relationship of nine species of the nike fish school (post-larva Gobioidei) in Gorontalo Bay waters, Indonesia. AACL Bioflux. 16(4): 2402-2408 **(7 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Saputro, K.E.A.; Hasim; Karlinasari, L.; Beik, I.S., (2023) Evaluation of sustainable rural tourism development with an integrated approach using MDS and ANP methods: case study in Ciamis, West Java, Indonesia. Sustainability. 15(3): 1-18 **(18 pages).**

Schoenfuss, H.L.; Blob, R.W., (2007). The importance of functional morphology for fishery conservation and management: applications to Hawaiian amphidromous fishes. Bishop Mus. Bull. Cult. Environ. Stud., 3: 125-141 **(18 pages).**

Silva, M.R.O.; Lopes, P.F.M., (2015). Each fisherman is different: taking the environmental perception of small-scale fishermen into account to manage marine protected areas. Mar. Policy. 51: 347-355 **(9 pages).**

Simanjuntak, C.; Baihaqi, F.; Prabowo, T.; Bilqis A, S.; Sulistiono, S.; Ervinia, A., (2021). Recruitment patterns of freshwater amphidromous fishes (Pisces: Gobiidae, Eleotridae) to the Cimaja estuary, Palabuhanratu Bay. Jurnal Iktiologi Indonesia. 21(3): 321-337 **(17 pages).**

Sutaman, S.; Wardiatno, Y.; Boer, M.; Yulianda, F., (2017). Assessment of sustainable use of coastal resources of regional waters conservation area Biak Numfor Regency, Papua Province, Indonesia. Ilmu Kelautan: Indonesian J. Mar. Sci., 22(2): 75-84 **(10 pages).**

Syamsuddin, S., (2021). Manajemen tempat pelelangan ikan (TPI) dalam meningkatkan pendapatan asli daerah (PAD) Kabupaten Sinjai. Jurnal Sosial dan Politik. 9(2): 124-132 **(9 pages).**

Teichert, N.; Valade, P.; Grondin, H.; Trichet, E.; Sardenne, F.; Gaudin, P., (2016). Pelagic larval traits of the amphidromous goby Sicyopterus lagocephalus display seasonal variations related to temperature in La Réunion Island. Ecol. Freshw. Fish. 25(2): 234-247 **(14 pages).**

Thuy, T.T.; My, N.H.; Hau, T.D., (2022). First faunal record of larval and juvenile gobies (Actinopterygii: Gobiiformes) in the Ka Long estuary, northern Vietnam. Acad. J. Biol., 44(1): 61–72 **(12 pages).**

Tietenberg, T.; Lewis, L., (2012). Environmental and Natural Resource Economics 9th Edition. Pearson Education Inc., New Jersey.

Widjaja, E.; Utomo, B.N.; Santoso, A.D.; Erlambang, Y.P.; Surono; Firmansyah, M.A.; Handoko, S.; Erythrina, E.; Rofiq, M.N.; Iskandar, D.; Sasongko, N.A.; Rochmadi, T.; Abbas, N.; Hanif, M.; Garno, Y.S.; Arianti, F.D.; Suretno, N.D.; Askinatin, M.; Hastuti, C.O.I.; Fahrodji, F., (2024). Sustainability index analysis for environmentally low-input integrated farming. Global J. Environ. Sci. Manage., 10(2): 1-20 **(20 pages).**

Yamasaki, N.; Kondo, M.; Maeda, K.; Tachihara, K., (2011). Reproductive biology of three amphidromous gobies, *Sicyopterus japonicus*, *Awaous melanocephalus*, and *Stenogobius* sp., on Okinawa Island. Cybium. 35(4): 345-359 **(15 pages).**

Yunus, R., (2014). Nilai-nilai Kearifan Lokal (Local Genius) sebagai Penguat Karakter Bangsa, Studi Empiris tentang Huyula. Deepublish, Yogyakarta.

Zhai, L.; Li, Z.; Wan, R.; Tian, S., (2023). Effects of Estuarine Environmental Heterogeneity on the Habitat of Gobiidea Species Larvae. Mar. Coast. Fish. 15: 1-13 **(13 pages).**

Zhang, G.; Lu, Y.; Fang, Z.; Yang, H.; Wei, Z. (2022). Analysis of the ecological carrying capacity of fish resources in Shengjin Lake, Anhui Province, China. Int. J. Environ. Res. Public Health. 19(13): 1-13 **(13 pages).**

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ORIGINAL RESEARCH ARTICLE

Environmental quality and macroeconomic phenomenon

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aimed to analyze the influence of economic growth, industrialization, government spending, and environmental taxes on environmental quality as well as the influence of environmental quality, unemployment, and inflation on Indonesia's economic growth. This condition is important to maintain environmentally friendly economic development to achieve sustainable development.
METHODS: The study was conducted using simultaneous equation model analysis considering classical assumption tests such as normality tests, granger causality and heteroscedasticity. This study data began in 2015 to 2021 in 34 provinces in Indonesia. In this study, the determinants of environmental quality used were industrialization, government spending and environmental taxes, whereas those of economic growth were unemployment and inflation.
FINDINGS: The results of the study indicate that economic growth, industrialization, government spending and environmental taxes have a significant effect on Indonesia's environmental quality. Collectively, these determinants account for 22.18 percent of the variance. However, environmental quality and unemployment do not have a significant effect on Indonesia's economic growth. Meanwhile, inflation has a significant effect on economic growth. Simultaneously, the influence of the determinants of economic growth is 33.52 percent.
CONCLUSION: Economic growth, industrialization, government spending and environmental taxes have a significant influence on Indonesia's environmental quality. On the other hand, environmental quality and unemployment do not have a significant effect on Indonesia's economic growth. Meanwhile, inflation has a significant effect on economic growth. The policies suggested, include the following 1) the government must be able to maintain environmental quality while still encouraging economic growth, implemented by creating an environmentally sound growth concept or applying the green economic concept to harmonize growth and the environment; 2) the industrialization process must be maintained so that it does not damage the environment, and pollution threshold rules created in the industrialization process must be applied.

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51

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NUMBER OF TABLES
8

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INTRODUCTION

Environmental problems have become a very serious topic of discussion and attention in the world (Umar *et al*., 2020; Mohadesi *et al.,* 2023; Samimi, 2024). Widespread pollution poses a real threat to industrialized countries, whereas quality of life until recently was measured almost solely by the growth of material output alone (Anwar *et al.*, 2020; Samimi and Nouri, 2023). Natural resource management should refer to aspects of environmental conservation and preservation. Exploitation of natural resources that is only economically oriented has not only positive economic effects but also negative effects for the continuity of human life. Economic growth targets and environmental quality improvement have become the main focus in achieving sustainable development carried out by organizations, governments and international institutions. In terms of energy use which is closely associated with carbon and pollution, it must be correlated with the improvement of industrial infrastructure to avoid detrimental impacts on human health, this step will lead to the reduction of global warming and thus requires countries to provide funding so that this goal can be achieved. One of the efforts made is strengthening the policy base to anticipate the risk of high emissions and reduce fossil energy to renewable energy globally (Dube and Horvey, 2023; Moghadam and Samimi, 2022). Environmental quality has made people aware of the importance of renewable energy which is more environmentally friendly (Samimi and Moghadam, 2024). Fiscal space in a country must focus on the energy transition in the long term in order to maintain production nationally and globally with policy mechanisms that lead to economic development (Raihan and Tuspekova, 2022; Appiah and Korankye, 2021). The process of achieving environmental sustainability needs to be adopted using a technological approach in processing natural resources in carrying out the framework as a policy function developed with an endogenous growth model in the scope of economic development (Aydın and Bayrak, 2016; Huo *et al*., 2023). Economic growth is a fundamental factor for analyzing a country's economic achievements. The composition of growth needs to be based on economic activities with the intensity of trade and industrialization both from within and outside the country. The opportunity to design economic activities based on the perspective of environmental sustainability is a challenge in itself for a country with a more innovative pattern. The development of a country that has achieved industrialization is encouraged to transform toward stages of large-scale economic change by providing policy alternatives that support these stages (Dogan *et al*., 2022; Tang *et al*., 2022). Productivity is seen as a factor to improve the level of the economy starting from investment which has an impact on the availability of capital, technological progress, trade and market expansion. This is very important for the process and quality of growth which will ultimately provide greater opportunities in the production scale which is supported by increased manufacturing capacity in industrialization so that it is able to produce the required goods and services (Varvarigos, 2023; Salman and Hosny, 2021; Azimi, *et al.,* 2019). One measure of whether the environmental quality of an area is good or not can be seen from the Indonesian Environmental Quality Index (IEQI) built by the Ministry of Environment and Forestry. This index is calculated from composite values in the form of water, air, land, and sea water quality indices. The temporary environmental quality index for 2021 is in the good range. Based on the trend since 2015, the environmental quality index tended to increase although it decreased in 2016 and 2018. A sharp increase occurred from 66.55 points in 2019 to 70.72 points in 2020 (Fig. 1).

Environmental quality is closely related to economic growth as in the long term production must consider the environment so that it is not damaged due to excessive exploitation of natural resources in achieving development targets (Shahbaz *et al*., 2019; Adu and Denkyirah, 2019).

As can be seen from Fig. 2, Indonesia's economic growth trend tends to improve from 2015 to 2021 before finally becoming -2.07 percent (%) in 2020. The rise and fall of the phenomenon of Indonesia's economic growth is caused by many factors, both economic and noneconomic factors. Of course, the phenomenon of economic growth has an impact on the quality of the environment itself. The phenomenon of environmental quality and economic growth has been investigated by many previous studies (Shahbaz *et al*., 2019; Anwar *et al*., 2020; Salman and Hosny, 2021). However, there are still very that examine the direct association between environmental quality and economic growth. This connection is important to see whether environmental quality and economic growth really influence each other or not, regardless of other factors that determine the focus of the two studies. Therefore, this study aimed to improve on previous studies by analyzing the association between environmental quality and

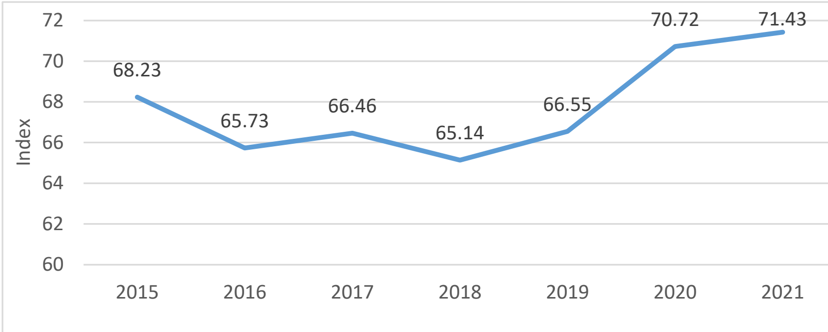

Fig. 1: Indonesian environmental quality index in 2015 to 2021 (Kementerian, 2022)

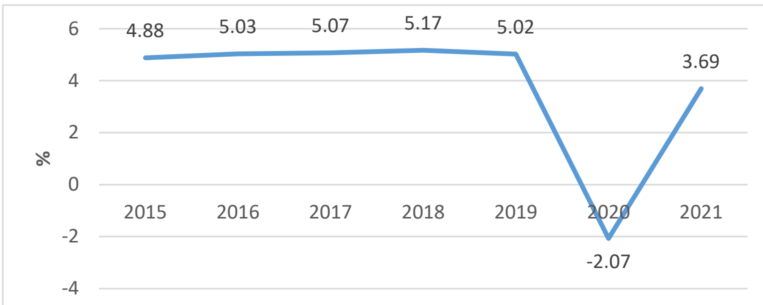

Fig. 2: Indonesia's economic growth in 2015 to 2021 (Badan Pusat Statistik, 2022)

economic growth and its determining factors. Based on the background above, this study analyzes the influence of industrialization, government spending and environmental taxes on environmental quality as well as the influence of unemployment and inflation on economic growth in Indonesia. This condition is important to analyze and maintain environmentally friendly economic development to achieve sustainable development. In general, the impact of economic growth on environmental quality varies in each country. Previous studies have demonstrated that there are positive and negative effects of economic growth on environmental quality. Shahbaz *et al*. (2019); Adu and Denkyirah, (2019); Andrei *et al*. (2016) reported the positive influence of economic growth on the environment. Andrei *et al*. (2016); Yazdi and Dariani, (2019) showed that economic growth can be negatively related to certain types of pollutants but not affected by certain pollutants or positively related to certain pollutants. Belaid and Youssef, (2017); Siregar *et al.* (2024); Rahman, (2020) showed that economic growth worsens the quality of the environment. Based on the findings above, it can be concluded that economic growth can exert a positive or negative effect on the quality of the environment. So what is the underlying positive and negative effect of economic growth on the quality of the environment? Theoretically, there are several aspects that underlie the positive and negative effects of economic growth. Feng *et al.* (2022); Peng *et al*. (2022) reported that environmental taxes and government spending have a positive effect on environmental quality. An increase in environmental taxes can provide an impetus for improving environmental quality, although it does not necessarily change significantly. Furthermore, government spending is based more on high income so that a country's fiscal policy can be directed toward maintaining environmental quality. Satrianto and Juniardi, (2023); Yamen *et al.* (2018) reported the importance of maintaining economic growth and industrialization in environmental sustainability. For decades, a country's development has focused on achieving high economic growth. However, this has a negative impact on the environment in the presence of strategic areas for economic development. In the long term, this risk will disrupt the sustainability of environmental quality as the higher levels of pollution affect the quality of good production and services. Furthermore, Opoku and Boachie, (2020); Lugina *et al*. (2022); D'agostino *et al.* (2016) explained the positive influence of government spending and environmental taxes on environmental quality. Economic policies that support environmental quality are urgently needed at this time. The high participation of technology in a country's development is a new problem that arises achieving low levels of carbon emissions. Energy use in the industrial sector receives special attention in the management of existing resources that have been the biggest contributor to environmental damage, be it air pollution, increased carbon and lack of energy efficiency. Kuo *et al*., (2022); Wang *et al*., (2022) reported the importance of environmental tax levies aimed at the decarbonization process in a country. Environmental quality is reflected in the levels of carbon, pollution and CO_2 which emphasize the importance of achieving a green energy-based economy. To minimize environmental damage, economic activity actors are able to provide accountability by providing costs for environmental taxes while focusing their production sector on the renewable energy sector to avoid ongoing climate change. Lu *et al*., (2023); Mandeya and Ho, (2021) explained their findings that inflation has a negative effect on economic growth. The production process begins with the provision of raw materials from various commodities at stable prices. Thus, to achieve economic growth, stable inflation in maintaining production supply is considered more effective in maintaining economic activity. High inflation must be avoided with price intervention from a country's government to ensure that the economy remains a driver of economic growth. Khan *et al*., (2020); Musibau *et al.*, (2021); Ozokcu and Ozdemir, (2017) aside from demonstrating the negative influence of economic growth on environmental quality, also reported the indirect influence of economic growth in the form of mitigation. Mitigation is a form of government policy to reduce pollution through pollution sources, so that economic growth is good for the environment. Based on this, it can be deduced that by increasing environmental regulations, economic growth can have a positive effect on environmental quality. The association between economic growth and environmental quality can be explained by the Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesis shows the association between economic growth and environmental degradation. The EKC hypothesis emerged in a study conducted Ozokcu and Ozdemir, (2017); Abdouli and Hammami, (2017) which examined the association between pollution levels and economic growth in 42 countries. Shahbaz *et al*., (2018); Yazdi and Dariani, (2019); Andrei *et al.*, (2016) reported that increasing income can increase environmental degradation, but an increase in income at a certain level will decrease environmental degradation. In graphical form, if environmental damage is the vertical axis (ordinate) and economic growth is the flat axis (abscissa), then the EKC will be shaped like an inverted_U (Fig. 2). The EKC pattern in the shape of an inverted U as seen in Fig. 2 is used as the basis for the argument that economic growth can improve environmental quality. Economic growth will initially reduce environmental quality (increasing environmental degradation), but at a certain point increasing economic growth will improve environmental quality (decreasing environmental degradation).

The association between economic growth and environmental quality through EKC can be explained through three effects scale, composition and technical. Scale effects are changes in environmental quality due to changes in output scale, composition effects are changes in environmental quality due to changes in the composition of producers (environmentally friendly and unfriendly), whereas technical effects are changes in environmental quality due to changes in government policy and techniques in production (Umar *et al*., 2020; Shahbaz *et al*., 2018; Belaid and Youssef, 2017; Musibau *et al.,* 2021). The working mechanism of these three effects adopts the assumption that pollution per output is constant. Economic growth can increase production activities thus, it can be deduced that economic growth increases a country's output scale. The production process always produces pollution because the latter is a coefficient of economic activity (Musibau *et al*., 2021; Yazdi and Dariani, 2019; Ssali *et al*., 2019). Economic growth can increase the scale of output and pollution, the coefficient of economic activity indicates that reducing the quality of the environment from economic growth has a scale effect. The composition effect is shown from changes in the composition of producers (environmentally friendly and nonenvironmentally friendly). Economic growth promotes increased specialization of production in sectors with comparative advantages, so that it will increase producers in these sectors. Based on this, the composition effect can have a negative impact on a country with a comparative advantage in a sector that produces relatively large amounts of pollution. This statement is based on the shift of producers toward sectors that tend to be less

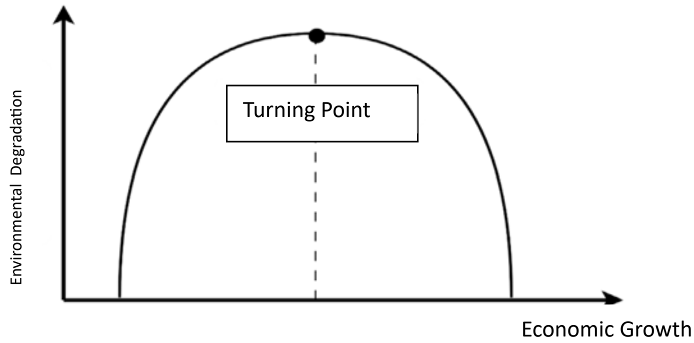

Fig. 3: Environmental Kuznet curve (Ozokcu and Ozdemir, 2017)

environmentally friendly, so that the composition of producers in the country yields more output from sectors that are relatively unfriendly. The third effect is the technical effect. As previously explained, technical effects are changes in environmental quality resulting from changes in policies and techniques in the production process. Changes in policy regarding the environment can occur due to pressure for specialization or public demand for better environmental quality. The most effective application of green economic indicators is a combination of resource efficiency (environmentally friendly indicators), energy efficiency with resource efficiency (social environmental indicators), and energy efficiency (socioeconomic indicators). Based on this, economic growth can encourage countries with comparative advantages in relatively dirty sectors, which can encourage governments to make policies that tend to harm the environment on the grounds of supporting superior sectors, thus having an impact on reducing the quality of the environment. Based on the aforementioned empirical and theoretical studies, relatively few have studied the association between environmental quality and economic growth simultaneously. It is important to establish this connection to determine whether environmental quality and economic growth actually influence each other, in addition to the factors that determine these two variables. This study aimed to develop previous research by analyzing the association between environmental quality and economic growth and its determining factors. Furthermore, it aimed to analyze the influence of determinants on environmental quality and economic growth in a model. The first hypothesis in this study is that economic growth, industrialization, government spending and environmental taxes significantly influence environmental quality. The second hypothesis is that environmental quality, unemployment and inflation significantly influence Indonesia's economic growth. This study was conducted in 34 provinces in Indonesia from 2015 to 2021.

MATERIALS AND METHODS

Method of the study

The data in this study are panel data sourced from the Indonesian Central Bureau of Statistics (BPS) and Indonesia Ministry of Environment and Forestry starting from 2015 to 2021 in 34 provinces in Indonesia. The amount of data in the study is 7 x 34 = 238.

Operational definition of the variables

Measurement of the data of each variable is presented in Table 1. The data was collected from the documentation, annual reports or records issued by the Indonesia BPS.

The equations in this study are as follows using Eqs. 1 and 2 (Shahbaz *et al*., 2019; Anwar *et al*., 2020; Salman and Hosny, 2021).

$$Y_{1t} = \alpha_0 + \alpha_1 Y_{2t} + \alpha_2 X_{1t} + \alpha_3 X_{2t} + \alpha_3 X_{3t} + \mu_{1t} \quad (1)$$

$$Y_{2t} = \beta_0 + \beta_1 Y_{1t} + \beta_2 X_{4t} + \beta_3 X_{5t} + \mu_{2t} \quad (2)$$

Meanwhile, the identification test with order conditions in this study is as follows using Eqs. 3 and 4 (Gujarati and Porter, 2009).

Equation 1: $K - k = 5 - 3 > m - 1 = 2 - 1 \rightarrow 2 > 1$ (overidentified) (3)

Equation 2: $K - k = 5 - 2 > m - 1 = 2 - 1 \rightarrow 3 > 1$ (overidentified) (4)

Table 1: Operational definition of the research variables

Variable	Measurement	Unit
Environmental quality (Y1)	Environmental Quality Index	Index/y
Economic growth (Y2)	GDP growth	%/y
Industrialization (X1)	GDP in Industry sector	Billion/y
Government expenditure (X2)	Total government expenditure	Billion /y
Environmental tax (X3)	Energy tax, transportation tax, pollution tax and resource tax	Billion /y
Unemployment (X4)	Number of unemployed people	%/y
Inflation (X5)	Changes in the prices of goods	%/y

Table 2: Normality test results for environmental quality equations

Notes	Score
Mean	8.430015
Median	0.792758
Maximum	22.70566
Minimum	-25.58398
S.D.	8.665549
Skewness	-0.354561
Kurtosis	3.021653
Jarque-Bera	4.278233
Probability	0.117759

Table 3: Normality test results for economic growth equation

Notes	Score
Mean	-4.700016
Median	0.482065
Maximum	21.95156
Minimum	-24.30739
S.D.	8.627782
Skewness	-0.324016
Kurtosis	2.943426
Jarque-Bera	3.596740
Probability	0.165569

RESULTS AND DISCUSSIONS

Results of classical assumption test

Based on data processing using the EViews 12 program, data processing results for various tests and analysis models were obtained as follows:

Normality test

The normality test is employed to determine whether the residuals of a situation are typically circulated. In the event that the residuals of a situation are not typically appropriated information fluctuation will be inhomogeneous. Thus, endeavors are expected to improve with the goal that the residuals are ordinarily dispersed. In view of the ordinariness test involving the Jarque_Bera technique on the equation for environmental quality and economic growth, it may be seen very well that the Jarque_Bera likelihood of an incentive for every situation is > 0.05. Based on the situation, environmental quality is 0.117759 and economic growth is 0.165569. Accordingly, it tends to be reasoned that the lingering condition for environmental quality and economic growth is typically circulated.

Granger causality test

This test can basically help determine whether a variable has a two-way relationship, or just a single course. In the event that the likelihood esteem is more modest than α = 0.05, the two factors (endogenous factors) have a two-way relationship or impact one another. Then again, in the event that the likelihood esteem is more prominent than α = 0.05, the two factors (endogenous factors) have a one-way relationship or do not impact one another.

Based on the results of the Granger causality test in Table 4, the probability value between environmental quality and economic growth is 0.0000 < 0.05 whereas that between economic growth and environmental quality is 0.0002 < 0.05. In other words, environmental quality variables on economic growth and economic growth on environmental quality have a two-way relationship or influence each other.

Heteroscedasticity

The heteroscedasticity test is used to determine whether the leftover change starting with one perception then onto the next is unique or the equivalent. Homoscedasticity is described as the event in which the leftover differences are very similar. The heteroscedasticity test in this exploration was conducted using the Glejser test strategy. In the event that the likelihood of an incentive for every variable is > α = 0.05, the condition does not contain heteroscedasticity problems. Contrarily, in the event that the likelihood of an incentive for every variable is < α = 0.05, the condition contains heteroscedasticity issues.

As can be seen from Tables 5 and 6, the probability value for each variable in each equation is > α = 0.05. Therefore, all equations in this study do not contain heteroscedasticity problems. In other words, in each equation there is the same variance of the residuals for all observations in each equation.

Estimation results of simultaneous equations

Environmental quality equation model

Table 7 presents the results of estimating the environmental quality equation. From the estimates that have been conducted, an environmental quality equation model is obtained as shown in Eq. 5 (Shahbaz *et al*., 2019; Anwar *et al*., 2020; Salman and Hosny, 2021).

$$Y_1 = 77.73 - 1.77\,Y_2 - 4.69\,X_1 - 8.56\,X_2 + 9.42\,X_3 \qquad (5)$$

In view of the assessment consequences of the natural quality condition shown above, with the assumption that financial development, industrialization, government spending and environmental taxes were missing, the environmental quality worth would be 77.73598 units. The R-squared worth of the natural quality condition is 0.221811. This indicates that the commitment of the factors financial development, industrialization, government spending and environmental taxes to environmental quality is 22.18%, and the excess of 77.82% is affected by different factors excluded from the environmental quality equation model. The direction of the influence of economic growth on environmental quality is negative with an estimated coefficient of -1.770236. This means that if economic growth increases by 1 unit, environmental quality will decrease by -1.770236 units assuming that other variables are constant (ceteris paribus). The direction of the influence of industrialization on environmental quality is negative with an estimated coefficient of -4.69E-05. This means that if industrialization increases by 1 unit, environmental quality will decrease by -4.69E-05 units (ceteris paribus). The direction of the influence

Table 4: Granger causality test results

Null Hypothesis	F-Statistic	Probabilities
Y2 does not Granger Cause Y1	12.84392	0.0000
Y1 does not Granger Cause Y2	9.79996	0.0002

Table 5: Heteroscedasticity test results for environmental quality equations

Variable	Probability	Description
Y2	0.9645	There is no heteroscedasticity
X1	0.4332	There is no heteroscedasticity
X2	0.5463	There is no heteroscedasticity
X3	0.3169	There is no heteroscedasticity

Table 6: Heteroscedasticity test results for economic growth equations

Variable	Probability	Description
Y1	0.1317	No heteroscedasticity occurs
X4	0.3151	No heteroscedasticity occurs
X5	0.7821	No heteroscedasticity occurs

Table 7: Estimated results of the effect of economic growth, industrialization and government spending on environmental quality in Indonesia

Variable	Coefficient	S.E.	t-Statistic	Prob.	R-squared	F-Statistic	Prob.(F-stat)
C	77.73598	7.172577	10.83794	0.0000			
Y2	-1.770236	0.427848	-4.13754	0.0009			
X1	-4.69E-05	1.16E-05	-4.05124	0.0001	0.221811	17.00507	0.000000
X2	-8.56E-10	2.54E-10	-3.37337	0.0022			
X3	9.42E-13	2.77E-13	3.40001	0.0016			

Table 8: Estimated results of the effect of environmental quality, unemployment and inflation on economic growth in Indonesia

Variable	Coefficient	S.E.	t-Statistic	Prob.	R-squared	F-Statistic	Prob.(F-stat)
C	1.690987	0.821589	2.058191	0.0409			
Y1	-0.068832	0.060659	-1.134737	0.2578	0.335165	13.86880	0.000000
X4	-1.43E-06	8.40E-07	-1.705618	0.0896			
X5	-0.164006	0.041188	-3.981842	0.0074			

of government spending on environmental quality is negative with an estimated coefficient of -8.56E-10. This means that if government spending increases by 1 unit, environmental quality will decrease by -8.56E-10 units (ceteris paribus). The direction of the influence of environmental taxes on environmental quality is positive with an estimated coefficient of 9.42E-13. This means that if environmental taxes increase by 1 unit, environmental quality will increase by 9.42E-13 units (ceteris paribus).

Economic growth equation model

Table 8 presents the results of simultaneous equation estimation of the economic growth equation. From the estimates that have been performed, an economic growth equation model is obtained as presented in Eq. 6 (Shahbaz *et al*., 2019; Anwar *et al*., 2020; Salman and Hosny, 2021).

$$Y_2 = 1.690987 - 0.068832\, Y_1 - 1.43E\text{-}06\, X_4 - 0.164006\, X_5 \quad (6)$$

In view of the assessment consequences of the monetary development condition presented above, with the assumption that environmental quality, unemployment and inflation were missing, the value of economic growth would be 1.690987 units. The R-squared value of the economic growth equation is 0.335165. This shows that the contribution of environmental quality, unemployment and inflation variables to economic growth is 33.5165%, and the remaining 66.4635% is influenced by other variables not included in the economic growth equation model.

The effect of environmental quality on economic growth is negative with an estimated coefficient of -0.068832. This means that if environmental quality increases by 1 unit, economic growth will decrease by -0.068832 units (ceteris paribus).

The effect of unemployment on economic growth is negative with an estimated coefficient of -1.43E-06. This means that if unemployment increases by 1 unit, economic growth will decrease by -1.43E-06 units (ceteris paribus). The effect of inflation on economic growth is negative with an estimated coefficient of -0.164006. This means that if inflation increases by 1 unit, economic growth will decrease by -0.164006 units (ceteris paribus).

Partial test

Partial tests are conducted to examine the influence of exogenous variables on endogenous variables in the partial regression equation by assuming that other variables are considered constant. It is also known as a probability test, this partial test. Rejecting H0 and accepting Ha indicate that there is a significant influence between the exogenous and endogenous variables if the probability value of the exogenous variable is less than $\alpha = 0.05$ (t-statistic ≥ t-table or – t-statistic < - t-table) on the endogenous variable. As opposed to this, Ha is rejected and H0 is accepted if the probability value of the exogenous variable on the endogenous variable is greater than $\alpha = 0.05$ (t-statistic ≥ - t-table or t-statistic < t-table). This suggests that there is no discernible association between the exogenous and endogenous variables. The probability value of every variable is visible based on the estimation results presented in Table 7. Environmental quality is affected by economic growth.. This is indicated by the probability value of economic growth on environmental quality of 0.0009 < α = 0.05. Therefore, partially, economic growth has a significant effect on environmental quality in Indonesia. On the other hand, industrialization has a significant effect on environmental quality in Indonesia with the probability value of 0.0001 or less than 0.05. Furthermore, government spending has a significant effect on environmental quality in Indonesia. This is indicated by the probability value of 0.0022 or less than 0.05. In addition, environmental taxes have a significant effect on environmental quality in Indonesia. This is indicated by the probability value 0.0016 or less than 0.05. Based on the estimation results in Table 8, the probability value of each variable can be seen. Environmental quality does not significantly influence economic growth in Indonesia. This is indicated by the probability value 0.2578 > α = 0.05. Also, unemployment does not have a significant effect on economic growth in Indonesia, indicated by the probability value of 0.0896 > α = 0.05. Then, inflation has a significant effect on economic growth in Indonesia. This is indicated by the probability value of inflation on economic growth of 0.0074 or less than 0.05. Therefore, inflation partially affects economic growth in Indonesia.

F test result

The effects of the exogenous variables on the endogenous ones are determined using the F test. According to the first hypothesis of the study, Indonesia's environmental quality is significantly impacted by government spending, industrialization, economic growth, and environmental taxation. The environmental quality equation's estimation findings yield an F-statistic probability value of 0.00000. Given that the environmental quality equation's probability value (F-statistic) is less than α = 0.05, it can be deduced that Indonesia's environmental quality is significantly impacted by government spending, industrialization, economic growth, and environmental taxes combined. This proves the alternative hypothesis in the first equation in this study. Thus, Indonesia's environmental quality is impacted by government spending, industrialization, economic growth, and environmental taxation. In Indonesia, there is a notable correlation between economic growth and environmental quality. The presence of a substantial association between economic growth and environmental quality suggests that economic expansion has an impact on environmental quality. Because of this, rising economic growth suggests higher levels of output of products and services. The increase in the production of goods and services has increased the demand for production inputs, one of which is an increase in demand for inputs from natural resources. Increasing input from natural resources without paying attention to the effects on the environment such as exploitation of mining products, deforestation, and water waste resulting in water pollution, will result in environmental damage. Attention needs to be paid to these effects so that in the future the desired growth does not damage the environment. However, this does not indicate that to maintain environmental quality, the economy does not need to grow, produce goods, and services. The economy needs to grow while of paying attention to environmental quality. The findings of the study support the hypothesis that there is a direct correlation between environmental quality and economic growth (Shahbaz *et al*., 2018; Anwar *et al*., 2020; Shahbaz *et al*., 2019; Siregar *et al*., 2024). In other words, increasing economic growth will have an impact on worsening environmental quality. Partially, industrialization also has a significant negative effect on environmental quality in Indonesia. The existence of a significant influence between environmental quality and industrialization indicates that the former is influenced by industrialization. Industrialization improves the processing of raw materials into semifinished and finished goods. This will accelerate the production of goods and increase waste. Uncontrolled waste will worsen the quality of soil, water, and air. In the end, the accumulation of waste will create more problems in environmental quality. The results of this study are consistent with the theory stating that there is an inverse association between industrialization and environmental quality. The uncontrolled acceleration of industrialization has an impact on the deterioration of environmental quality. The results of this study are also consistent with those of previous research (Nasrollahi *et al*., 2020). Furthermore, government spending shows a significant negative influence on environmental quality in Indonesia, partially. The fact that there is a significant correlation between government spending and environmental quality suggests that government spending has an impact on environmental quality. This requirement stems from the fact that higher government spending will promote higher levels of production capacity for both products and services. These improvements can be in the form of building roads, bridges, irrigation, electricity, networks, ports, and airports. This increase in spending can increase the use of production inputs such as river dredging, deforestation, and gas disposal. If this cannot be properly controlled, productive government spending to encourage the real sector will have a negative impact on the environment. On the other hand, if government spending can be controlled by paying attention to environmental quality, this condition can have a positive impact on the environment. The findings of this study support the hypothesis that expenditure by the government degrades the quality of the environment. Research findings also corroborate the results of the studies by Baz *et al*., (2020); Andrei *et al*., (2016); Abdouli and Hammami, (2017) which conclude that uncontrolled government spending can damage the environment. Notably, there is a positive correlation between environmental taxes and the quality of the environment in Indonesia, albeit indirect. It can be deduced that environmental taxation has an impact on environmental quality because there is a considerable correlation between the two variables. This is because firms are required to pay environmental taxes, which are mandatory contributions. Environmental taxes will cause additional costs by companies or producers in producing goods and services. Companies will consider their behavior if they want to pollute the environment because environmental taxes will increase if there are actions that can pollute the environment. Certainly, this situation will be able to protect the environment from damage. On the other hand, if environmental taxes are not properly implemented, companies will be free to pollute the environment. In the end, this condition can damage environmental quality. The results of this study are consistent with the theory that environmental taxes can change the behavior of agents to damage the environment. Effective implementation of environmental taxes can help improve environmental quality. This result is also supported by studies conducted by Andrei *et al*., (2016); Khan *et al*., (2020); Shahbaz *et al*., (2019); Adu and Denkyirah, (2019) which conclude that environmental taxes contribute to the improvement of the environment. Environmental taxes can discourage agents' desire to pollute the environment. As reported by Oryani *et al.,* (2022) efforts to improve environmental quality include reducing emissions from energy consumption, creating policies to manage energy consumption by increasing public awareness of the environment, diversifying the energy mix, and implementing laws regarding subsidies. The second hypothesis in this study states that environmental quality, unemployment and inflation have a significant effect on economic growth in Indonesia. From the estimation results of the economic growth equation, a probability value (F-statistic) of 0.00000 is obtained. Because the probability value (F-statistic) in the economic growth equation is $< \alpha = 0.05$, it can be said that environmental quality, unemployment, and inflation have a significant effect on economic growth in Indonesia. The existence of the alternative hypothesis in the second equation in this study has been partially proven. Thus, environmental quality, unemployment, and inflation affect economic growth in Indonesia. Furthermore, environmental quality does not have a significant effect on economic growth in Indonesia. The lack of a significant correlation between environmental quality and economic growth suggests that environmental quality has a negligible effect on economic growth. This requirement from the fact that environmental quality influences economic activity as a result of environmental quality rather than being a cause of economic system. Good environmental quality has little effect on promoting rapid economic growth. Despite the fact that economic growth is still measured in association with the environment. Thus, even while environmental quality is improving, it will not have an effect on economic growth. Findings of this study are consistent with theory and research findings indicating that environmental quality cannot affect or have an influence on economic growth (Adu and Denkyirah, 2019; Ozokcu and Ozdemir, 2017; Rahman, 2020). Partially, unemployment does not significantly affect economic growth in Indonesia. The lack of a substantial correlation between unemployment and economic growth suggests that unemployment has a negligible effect on growth. This is because unemployed individuals represent the portion of the labor force that is not employed and hence not productive. Because unemployment does not result in the production of goods and services, it does not support economic expansion. In actuality, economic welfare is decreased by the presence of unemployment. Consequently, there is no association between the unemployment rate and economic growth indeed, labor plays a role in the process of economic output production. The findings of this study support Solow's theory in another way, which holds that labor, not unemployment, is what drives economic expansion. The findings of this study also support previous research suggesting that unemployment has no bearing on economic growth (Adelowokan *et al.*, 2019; Louail and Riache, 2019).

Furthermore, Indonesia's economic growth is severely hampered by inflation. The fact that there is a substantial correlation between inflation and economic growth suggests that inflation affects economic growth. The purchasing power of people may decrease when inflation increases. Weakening purchasing power will result in a decline in public consumption. Consumption as a factor in the demand for goods and services will reduce the production of the goods and services themselves. This transmission effect will ultimately result in a decline in economic growth. Although inflation is also required to spur growth, uncontrolled inflation can suppress the rate of growth itself. Conversely, low and relatively stable inflation can maintain people's purchasing power so that people's consumption remains sustainable. Certainly, this situation will be able to maintain Indonesia's economic growth in a better direction. The findings of this study are consistent with earlier hypotheses and investigations into the impact of inflation on economic growth. These findings suggest that inflation hinders economic expansion. Growing inflation will impede economic expansion (Azam and Khan, 2022; Sanga *et al*., 2022; Satrianto and Juniardi, 2023).

CONCLUSION

Based on the results of the study and discussion in the previous section, this research concludes that economic growth, industrialization, government spending and environmental taxes significantly influence on the quality of the environment in Indonesia. The contribution of the influence of economic growth, industrialization, government spending, and environmental taxes on environmental quality is 22.18%. Partially, the influence of economic growth on environmental quality -1.770236 per unit; industrialization -4.69E-05 per unit; government spending -8.56E-10; and environmental taxes 9.42E-13 per unit. Economic growth, industrialization, and government spending have a negative effect on environmental quality. This means that increasing economic growth, industrialization, and government spending have an impact on the reduction of environmental quality. On the other hand, environmental quality and unemployment do not have a significant effect on economic growth in Indonesia. Fluctuations in environmental quality and unemployment do not influence the ups and downs of economic growth. Meanwhile, inflation has a significant and negative influence on economic growth. This indicates that an increase in inflation will reduce economic growth by -0.164006 units. This implies that fluctuations in unemployment and environmental quality have no bearing on changes in Indonesia's rate of economic growth. Meanwhile, economic growth is significantly impacted by inflation. A rise in inflation will lead to a decline in economic growth. On the other hand, sloping and declining inflation will encourage increased economic growth in Indonesia. The policies that can be suggested from the results of this study are as follows: the government must be able to maintain environmental quality while still encouraging economic growth. This policy can be implemented by creating an environmentally sound growth concept. This concerns efforts to utilize natural resources while maintaining aspects of environmental maintenance and preservation. This environmentally friendly development prioritizes sustainable development that optimizes the benefits of natural resources and human resources by harmonizing human activities with the ability of natural resources to support them. This condition can be realized by implementing binding laws or regulations in each region in Indonesia. The government must be able to maintain the industrialization process to avoid damaging the environment. This can be done by applying the pollution threshold rules created by the industrialization process. The government can continue to maintain productive spending, particularly on spending that can improve environmental quality. Environmental taxes are an effective instrument in maintaining environmental quality during the study period. Therefore, the implementation of environmental tax policies can continue to be improved in the future to ensure improvement in environmental quality. Furthermore, the government must be able to ensure stable inflation so that it does not have a negative impact on economic growth. Management of the supply and demand sides of goods and services needs to be controlled so that prolonged inflation does not occur, which negatively affects Indonesia's economic growth.

AUTHOR CONTRIBUTIONS

S. Amar has roles in Conception and design, Critical revision of the manuscript for important intellectual content, Obtaining funding and Supervision. A. Satrianto has roles in Conception and design, Analysis and interpretation of data, Drafting of the manuscript, Critical revision of the manuscript for important intellectual content, Statistical analysis, Obtaining funding and Supervision. Ariusni has a role in Drafting of the manuscript, and Critical revision of the manuscript for important intellectual content. A. Ikhsan has a role in Analysis and interpretation of data, Statistical analysis, and Administrative, technical, or material support. E.S Siregar has a role in acquisition of data, statistical analysis, and administrative, technical, or material support.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication, and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
+	Plus sign
=	Equal sign
≥	greater than or equal to
-	Minus sign
/	Per
A	Alpha
BPS	Central Bureau of Statistics
E	Error term
EKC	Environmental Kuznets Curve
Eq	Equation
et al.	Et alia
F-test	A statistical test that is used in hypothesis testing to check whether the variances of two populations or two samples are equal or not
F-Statistic	A ratio of two variances
Fig.	Figure
GDP	Gross domestic product
i	Cross-section
IEQI	Indonesian environmental quality index
Prob.	Probability
Prob.(F-stat)	Probability F Statistic
R-squared	The coefficient of determination
S.D.	Standard deviation
S.E.	Standard error
t	Time series
t-Statistic	Hypothesis test statistic
X1	Industrialization
X2	Government expenditure
X3	Environmental tax
X4	Unemployment
X5	Inflation
y	Year
Y	Endogenous variable
Y1	Environmental quality
Y2	Economic growth

REFERENCES

Abdouli, M.; Hammami, S., (2017). Investigating the causality links between environmental quality, foreign direct investment and economic growth in mena countries. Int. Bus. Rev., 26(2): 264–278 **(15 pages)**.

Adelowokan, O.A.; Maku, O.E.; Babasanya, A.O.; Adesoye, A.B., (2019). Unemployment, poverty and economic growth in nigeria. J. Econ. Manage., 35(1): 5–17 **(13 pages).**

Adu, D.T.; Denkyirah, E.K., (2019). Economic growth and environmental pollution in west Africa: testing the environmental kuznets curve hypothesis. Kasetsart J. Soc. Sci., 40(2): 281–288 **(8 pages).**

Andrei, J.; Mieila, M.; Popescu, G.H.; Nica, E.; Cristina, M., (2016). The impact and determinants of environmental taxation on economic growth communities in romania. Energies. 9(11): 1–11 **(11 pages).**

Anwar, A.; Younis, M.; Ullah, I., (2020). Impact of urbanization and economic growth on CO2 emission: A case of far east Asian countries. Int. J. Environ. Res. Public Health, 17(7): 1-8 **(8 pages).**

Appiah, M.; Li, F.; Korankye, B., (2021). Modeling the linkages among CO_2 emission, energy consumption, and industrialization in sub-saharan african (SSA) countries. Environ. Sci. Pollut. Res. Int., 28(29): 38506–38521 **(16 pages).**

Aydın, C.; Esen, O.; Bayrak, M., (2016). Inflation and economic growth: a dynamic panel threshold analysis for Turkish republics in transition process. Procedia Social Behav. Sci., 229 : 196–205 **(10 pages).**

Azam, M.; Khan, S., (2022). Threshold effects in the relationship between inflation and economic growth: further empirical evidence from the developed and developing world. Int. J. Fin. Econ., 27(4): 4224–4243 **(20 pages).**

Azimi, N.; Azimi, P.; Samimi, M.; Mansouri Jalilian, T., (2019). Ultrasonic-assisted adsorption of Ni (II) ions from aqueous solution onto Fe3O4 nanoparticles. Adv. Nanochem., 1(2): 66-72 **(7 pages).**

Badan Pusat Statistik. (2022). Statistik indonesia 2022. Badan Pusat Statistik.

Baz, K.; Xu, D.; Ali, H.; Ali, I.; Khan, I.; Khan, M.M..; Cheng, J., (2020). Asymmetric impact of energy consumption and economic growth on ecological footprint: using asymmetric and nonlinear approach. Sci. Total Environ., 718: 1-32 **(32 pages).**

Belaid, F.; Youssef, M., (2017). Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: assessing the evidence from algeria. Energy Policy. 102: 277–287 **(11 pages).**

D'Agostino, G.; Dunne, J.P.; Pieroni, L., (2016). Government spending, corruption and economic growth. World Dev., 84: 190–205 **(16 pages).**

Dogan, B.; Chu, L.K.; Ghosh, S.; Truong, H.H.D.; Lorente, D.B., (2022). How environmental taxes and carbon emissions are related in the G7 economies?. Renew. Energy, 187: 645–656 **(12 pages).**

Dube, A.; Horvey, S.S., (2023). Institutional quality and renewable energy capital flows in Africa. Future Bus. J., 9(55): 1-16 **(16 pages).**

Feng, H.; Liu, Z.; Wu, J.; Iqbal, W.; Ahmad, W.; Marie, M., (2022). Nexus between government spending's and green economic performance: role of green finance and structure effect. Environ. Technol. Innov., 27(102461): 1-16 **(16 pages).**

Gujarati, D.N.; Porter, D.C., (2009). Basic econometrics fifth edition. Mc Graw Hill Series. **(922 pages).**

Huo, C.; Hameed, J.; Albasher, G.; Pang, M., (2023). The impact of institutional quality, natural resources, and finance-growth on china's economic recovery: an empirical study. Resour. Policy. 83(103740) 1-10 **(10 pages).**

Kementerian, L.H.K., (2022). Indeks kualitas lingkungan hidup indonesia. Kementerian Lingkungan Hidup dan Kehutanan. 1-70 **(70 pages).**

Khan, M.K.; Khan, M.I.; Rehan, M., (2020). The relationship between energy consumption, economic growth and carbon dioxide emissions in pakistan. Financ. Innov., 6(1) : 1–13 **(13 pages).**

Kuo, Y.; Maneengam, A.; The, C.P.; An, N.B.; Nassani, A.A.; Haffar, M.; Qadus, A., (2022). Fresh evidence on environmental quality measures using natural resources, renewable energy, non-renewable energy and economic growth for 10 Asian nations from cs-ardl technique. Fuel. 320(123914): 1-10 **(10 pages).**

Louail, B.; Riache, S., (2019). Asymmetry relationship between economic growth and unemployment rates in the Saudi economy: application of okun's law during the period 1991-2017. Int. J. Adv. Appl. Sci., 6(10) : 83–88. **(6 pages).**

Lu, X.; Farhani, S.; Soliman, A.M.; Zhou, C.; Su, K., (2023). Renewable energy consumption, trade and inflation in mena countries with augmented production function: implications for the cop26. Technol. Forecasting Soc. Change, 194(122712): 1-10 **(10 pages).**

Lugina, E.J.; Mwakalobo, A.B.S.; Lwesya, F., (2022). Effects of industrialization on tanzania's economic growth: A case of manufacturing sector. Future Bus. J., 8(62): 1–11 **(11 pages).**

Mandeya, S.M.T.; Ho, S.Y., (2021). Inflation, inflation uncertainty and the economic growth nexus: an impact study of South Africa. MethodsX, 8(101501): 1-17 **(17 pages).**

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages).**

Mohadesi, M.; Gouran, A.; Darabi, F.; Samimi, M., (2023). Sunflower seed pulp ash as an efficient and eco-friendly adsorbent for Congo red uptake: characteristics, kinetics, and optimization. Water Pract. Technol., 18 **(12 pages).**

Musibau, H.O.; Shittu, W.O.; Ogunlana, F.O., (2021). The relationship between environmental degradation, energy use and economic growth in Nigeria: new evidence from non-linear ARDL. Int. J. Energy Sect. Manage., 15(1): 81–100 **(20 pages).**

Nasrollahi, Z.; Hashemi, M.S.; Bameri, S.; Taghvaee, V.M., (2020). Environmental pollution, economic growth, population, industrialization, nd technology in weak and strong sustainability: using stirpat model. Environ. Dev. Sustain. 22: 1105–1122 **(18 pages).**

Opoku, E.E.O.; Boachie, M.K., (2020). The environmental impact of industrialization and foreign direct investment. Energy Policy. 137(111178): 1-12 **(12 pages).**

Oryani, B.; Kamyab, H.; Moridian, A.; Azizi, Z.; Rezania, S.; Chelliapan, S., (2022). Does structural change boost the energy demand in a fossil fuel-driven economy? New evidence from Iran. Energy. 254(124391): 1-12 **(12 pages)**

Ozokcu, S.; Ozdemir, O., (2017). Economic growth, energy, and environmental kuznets curve. Renew. Sustain. Energy Rev., 72: 639–647 **(9 pages).**

Peng, D.; Li, R.; Shen, C.; Wong, Z., (2022). Industrial agglomeration, urban characteristics, and economic growth quality: the case of knowledge-intensive business services. Int. Rev. Econ. Fin., 81: 18–28 **(11 pages).**

Rahman, M.M., (2020). Environmental degradation: the role of electricity consumption, economic growth and globalisation. J. Environ. Manage., 253(109742): 1-8 **(8 pages).**

Raihan, A.; Tuspekova, A., (2022). Toward a sustainable environment: nexus between economic growth, renewable energy use, forested area, and carbon emissions in malaysia. Resour. Conserv. Recycl. Adv., 15(200096): 1-11 **(11 pages).**

Salman, D.; Hosny, N.A., (2021). The nexus between Egyptian renewable energy resources and economic growth for achieving sustainable development goals. Future Bus. J., 7(47): 1-12 **(12 pages).**

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Samimi, M.; Moghadam, H., (2024). Modified evacuated tube collector basin solar still for optimal desalination of reverse osmosis concentrate. Energy, 289: 129983 **(8 pages).**

Sanga, G.J.; Kongolo, M.; Mnongya, R., (2022). Effect of inflation on economic growth in tanzania for the period from 1970 to 2020. Int. Res. J. MMC, 3(5): 12–27 **(16 pages).**

Satrianto, A.; Juniardi, E., (2023). Inclusive human development and inclusive green growth: a simultaneous approach. Int. J. Sustain. Dev. Plann., 18(2): 523–530 **(8 pages).**

Shahbaz, M.; Haouas, I.; Hoang, T.H.V., (2019). Economic growth and environmental degradation in vietnam: is the environmental kuznets curve a complete picture. Emerg. Mark. Rev., 38: 197–218 **(22 pages).**

Shahbaz, M.; Nasir, M.A.; Roubaud, D., (2018). Environmental degradation in france: the effects of fdi, financial development, and energy innovations. Energy Econ., 74: 843–857 **(15 pages).**

Siregar, E.S.; Sentosa, S.U.; Satrianto, A., (2024). An analysis on the economic development and deforestation. Glob. J. Environ. Sci. Manage., 10(1) : 355–368 **(14 pages).**

Ssali, M.W.; Du, J.; Mensah, I.A.; Hongo, D.O., (2019). Investigating the nexus among environmental pollution, economic growth, energy use, and foreign direct investment in 6 selected sub-Saharan african countries. Environ. Sci. Pollut. Res. Int., 26(11): 11245–11260 **(16 pages).**

Tang, D.; Li, Y.; Zheng, H.; Yuan, X., (2022). Government R&D spending, fiscal instruments and corporate technological innovation. China J. Acc. Res., 15(3): 1-32 **(32 pages).**

Umar, M.; Ji, X.; Kirikkaleli, D.; Shahbaz, M.; Zhou, X., (2020). Environmental cost of natural resources utilization and economic growth: can china shift some burden through globalization for sustainable development?. Sustain. Dev., 28(6): 1678–1688 **(11 pages).**

Varvarigos, D., (2023). Cultural persistence in corruption, economic growth, and the environment. J. Econ. Dyn. Control. 147(104590): 1-21 **(21 pages).**

Wang, W.; Rehman, M.A.; Fahad, S., (2022). The dynamic influence of renewable energy, trade openness, and industrialization on the sustainable environment in G-7 economies. Renew. Energy. 198 : 484–491 **(8 pages).**

Yamen, A.; Allam, A.; Bani M.A.; Uyar, A., (2018). Impact of institutional environment quality on tax evasion: a comparative investigation of old versus new eu members. J. Int. Account. Aud. Taxation. 32: 17–29 **(13 pages).**

Yazdi, S.K.; Dariani, A.G., (2019). CO_2 emissions, urbanisation and economic growth: evidence from Asian countries. Econ. Res. Ekonomska Istrazivanja. 32(1) : 510–530 **(21 pages).**

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ORIGINAL RESEARCH PAPER

Degradation of low-density polyethylene by a novel strain of bacteria isolated from the plastisphere of marine ecosystems

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ABSTRACT

BACKGROUND AND OBJECTIVES: Low-density polyethylene is one of the dominant recalcitrant plastic pollutants in the ocean, thus causing complicated problems. Biodegradation is an efficient, environmentally friendly, and sustainable option to overcome these problems. This study aims to quantitatively and qualitatively analyze the ability of marine bacterial isolates to degrade low-density polyethylene plastic.

METHODS: Bacteria were isolated from plastic samples using serial dilution technique and inoculated on media containing low-density polyethylene powder. Bacterial degradation ability was analyzed quantitatively based on weight loss percentage and energy-dispersive X-ray spectroscopy values, as well as qualitatively based on changes in physical and chemical structures using Scanning Electron Microscopy and Fourier transform infrared spectroscopy. Meanwhile, bacterial isolates were identified based on gene sequence and phylogenetic analyses.

FINDINGS: Four bacterial isolates were isolated from low-density polyethylene plastic samples. Quantitative analysis found that the low-density polyethylene film experienced weight loss up to 10-15 percent during 35 days of incubation, with a maximum daily weight loss rate of 0.004 milligrams per day, meaning that the four bacterial isolates have the potential to degrade plastic. Meanwhile, qualitative analysis based on Scanning Electron Microscope observations revealed changes in the physical structure of the film surface in the form of a rough surface, formation of holes, and breakdown into clumps across the film surface. Variations in these changes were tested. In the control, no changes occurred and the film surface remained flat and smooth. Conversely, the results of the energy dispersive X-ray spectroscopy spectrum analysis showed that the low-density polyethylene film broke down into smaller fragments, characterized by a decrease in mass from 98.51 percent to 98.23 percent. Fourier transform infrared observations showed variations in transmittance and wavenumbers, indicating changes in chemical bonds or functional groups in the low-density polyethylene film which caused it to become brittle and break down into smaller fragments with a lower molecular weight, making it easier for bacteria to digest. The results of the gene sequence analysis identified four bacterial isolates, namely *Lysinibacillus* sp. IBP-1, Bacillus sp. IBP-2, *Bacillus paramycoides* IBP-3, and Bacillus cereus IBP-4. Based on the quantitative and qualitative analyses, the ability of the bacterial isolates to degrade low-density polyethylene film was shown in the following order: *Bacillus paramycoides* IBP-3 > Bacillus cereus IBP-4 > *Lysinibacillus* sp. IBP-1 > *Bacillus sp*. IBP-2.

CONCLUSION: All four marine bacterial isolates can use low-density polyethylene as the sole carbon source. Based on quantitative and qualitative analyses, *Bacillus paramycoides* IBP-3 has the best potential for degrading low-density polyethylene film. This study provides information on potential bacterial isolates that can be developed to control low-density polyethylene plastic waste.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
57	8	2

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INTRODUCTION

Plastic is a synthetic polymer composed of long carbon chains with stable chemical bonds. It is lightweight, resistant to moisture and certain chemicals, flexible, malleable, and hydrophobic (Sekhar *et al.,* 2016). Due to its practical nature, plastic has become an important part of human life with its widespread use, automatically affecting plastic production (Danso *et al.,* 2019). World plastic production reaches 335 million tons per year (mt/y) (Gupta and Devi, 2019). According to data from the Director General of Chemical, Pharmaceutical, and Textile Industries of the Ministry of Industry, Indonesia's plastic production target in 2020-2024 is estimated to reach 6.85-10.03 million tons, with consumption of around 25-40 kilograms per capita per year (kg/capita/year) (IKFT-KP, 2019). However, the use of plastic without proper management accelerates the rate of plastic waste generation in the environment. Based on the National Waste Management Information System of the Ministry of Environment and Forestry of the Republic of Indonesia, Indonesia generates 12.83 million tons of waste per year, with a plastic waste composition of 19.11 percent (%) (SIPSN KLHK, 2023). Commonly used plastic waste management methods include incineration (12%) and recycling (9%), while the remaining 79% accumulates in the environment (Khandare *et al.,* 2022; Geyer *et al.,* 2017). Nonetheless, incineration results in air pollution as it releases harmful gases such as carbon monoxide, furans, dioxins, sulfur dioxide, nitrous oxide, and carbon dioxide in the air, thus causing respiratory and immune disorders (Gangwar *et al.,* 2019; Cheng *et al.,* 2020). Furthermore, around 32% of plastic waste accumulated in landfills ends up in the ocean (Delacuvellerie *et al.*, 2019). Low-density polyethylene (LDPE) is one of the most widely used types of plastic in the world and is most commonly found in the ocean (Pinto *et al.,* 2022). LDPE has a higher molecular weight, so it takes a long time to decompose in the environment (Gupta and Devi, 2020; Li *et al.,* 2020; Raddadi and Fava, 2019). The presence of LDPE in the marine environment can cause marine pollution, endanger marine animals, disrupt the ecological balance, and damage marine ecosystems (Varó *et al.,* 2021; Yang *et al.,* 2021). Several studies have reported solutions for degrading LDPE plastic waste using bacteria which are considered more effective and environmentally friendly (Taghavi *et al.,* 2021; Asiandu *et al.,* 2021). Among these methods is the potential use of *Bacillus cereus* NJD 1 (strain code) isolated from landfills to degrade LDPE with a weight loss percentage (W%) of 43 for 120 days (Jayan *et al.,* 2023). A study of *Marinobacter* sp H-244, *Marinobacter* sp H-246, and *Bacillus subtilis* H-248 found that these three identified marine bacterial isolates can degrade LDPE film, with a maximum W% of up to 1.68 within 90 days of degradation by *Marinobacter* sp H-246 (Khandare *et al.,* 2022). In addition, another previous study reported that three of the six tested marine bacterial isolates were able to degrade LDPE film after incubation for 30 days, namely *Kocuria palustris* M16, *Bacillus pumilus* M27, and *Bacillus subtilis* H1584, with W% of 1%, 1.5%, and 1.75%, respectively (Sangeetha Devi *et al.,* 2019).

Based on the above explanation, the development of a microbial-based plastic waste management method is a wise and environmentally friendly option. In recent decades, studies on the biodegradation of plastic waste have gained great popularity and have been widely conducted. Bacteria that have been proven to be able to degrade various types of plastics, such as PE, LDPE, and others, include *Bacillus, Rhodococcus, Chelatococcus, Comamonas, Pesudomonas, Paenibacillus,* and *Ideonella* isolated from various polluted locations. These bacteria can degrade plastics by producing diverse extracellular enzymes, such as esterase, protease, glycoside, and hydrolases (Yuan *et al.,* 2020). Enzymatic degradation does not harm the environment because it works on specific substrates, thus being considered better, more environmentally friendly, and safer (Roohi *et al.,* 2017). So far, information regarding the degradation of LDPE plastic, both physically and biologically, by marine microorganisms is still limited. Therefore, it is crucial to conduct a study on this topic to contribute to the existing literature. This study aims to discover new bacterial isolates from LDPE plastic waste floating in the ocean in Indonesia. Marine bacteria were chosen as they are more tolerant of various physical and chemical environmental conditions, with high variability. In addition, marine bacteria are more adaptive to exposure to plastic waste accumulating in the ocean. In this study, marine bacterial isolates that have the potential to act as biodegradation agents were tested quantitatively and qualitatively in the laboratory to be further developed and widely used for environmental bioremediation of LDPE plastic

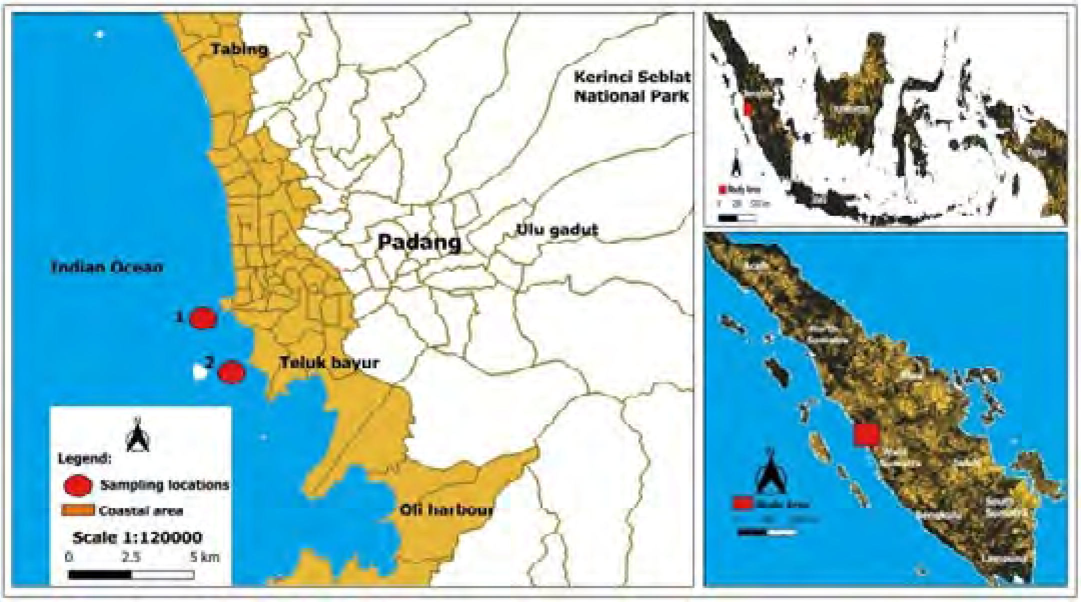


Fig. 1: Geographic location of the study area for marine plastic sampling at Padang Beach, Indonesia

contamination. This study was conducted in coastal Padang City, West Sumatra, Indonesia in 2023.

MATERIALS AND METHODS

Sampling and isolation of marine bacteria for LDPE degradation

In this study, seawater and LDPE plastic sediment samples were taken from two stations (S1 and S2), namely Purus Beach (0°55'57.8"S 100°35'00.1"E) and Padang Beach (0°56'01.3"S 100°21'00.9"E) located on the coast of Padang City, West Sumatra, Indonesia, as shown in Fig. 1. The description of sampling stations is as follows: Purus Beach (S1) is a tourist attraction which is the estuary where the Bandar Purus River meets the Padang Beach. Meanwhile, Padang Beach (S2) is the center of Padang City beach tourism activities which is visited by many domestic and foreign tourists. Samples were taken in April 2023, during the dry season in the region. Samples were taken from sea depths of 0-30 cm and stored in a cool box for further analysis.

Marine bacteria were isolated using media in grams per liter (g/L) consisting of 1 g/L LDPE powder, 0.05 g/L peptone, 15 g/L bacto agar, and 3.5% NaCl. Isolation was performed using a serial dilution technique and inoculation with a pour plate, and incubation was carried out at room temperature, approximately 25 degrees Celsius (25°C). Morphologically distinct colonies were purified on streak plates to obtain pure isolates (Khandare *et al*., 2022). The flowchart of the complete stages of this study procedure can be seen in Fig. 2.

Preparation of LDPE film biodegradation by marine bacterial isolates for quantitative and qualitative analyses

LDPE plastic was collected from the sea with a size of about 10 x 15 cm. Then, the LDPE plastic was prepared for testing by reducing its size to 1x1 square centimeter (cm^2) and sterilizing it using a washing solution of 7 milliliters (mL) tween 80, 10 mL bleach, and 983 mL distilled water for one hour. After that, the LDPE film was rinsed with sterile distilled water 2-3 times to remove any remaining washing solution. The LDPE film was surface sterilized with 70% isopropanol and aseptically transferred into a sterile petri dish to dry overnight (Khandare *et al*., 2022; Sudhakar *et al*., 2008).

Biodegradation of LDPE film by marine bacterial isolates

Sterile LDPE film that has been previously weighed as initial weight data was aseptically inserted into Bushnell Haas medium with the following

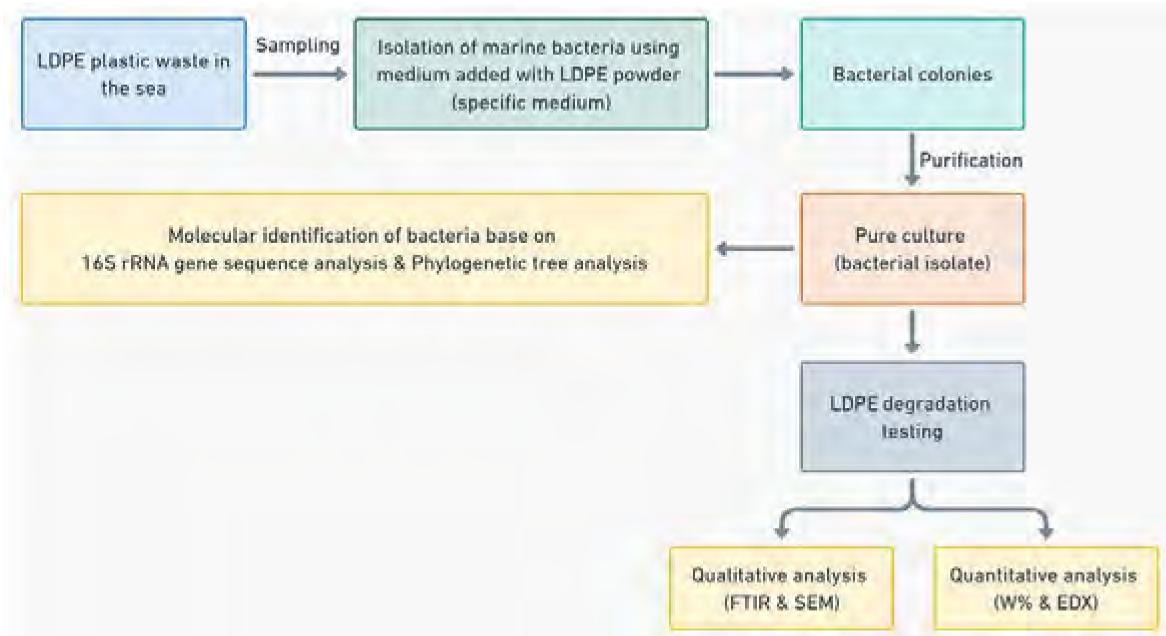


Fig. 2: Flowchart of the current study

composition (g/L): 1.0 ammonium nitrate (NH_4NO_3), 0.2 magnesium sulfate heptahydrate ($MgSO_4$ $7H_2O$), 1.0 dipotassium phosphate (K_2HPO_4), 0.1 calcium chloride dihydrate ($CaCl_2.2H_2O$), and 0.15 potassium chloride (KCl). Then, 3.5% NaCl was added to the medium. Each marine bacterial isolate was inoculated separately at 10% volume per volume (v/v). The inoculum density was adjusted to 1.5 x 10^6 colony-forming units per milliliter (cfu/mL), and a control study was carried out without adding inoculum. The study was conducted in 3 replicates, incubated for 35 days on a shaker with a rotation speed of 120 per minute (120 rpm) at room temperature (Khandare *et al*., 2022).

Harvesting of LDPE film after biodegradation

After the biodegradation process, the LDPE film was removed and rinsed with 2% sodium dodecyl sulfate (SDS) solution to remove the residual cells and medium. Then, the LDPE film was rinsed with sterile distilled water three times and dried overnight. The LDPE film was weighed to obtain its final weight after biodegradation for the quantitative and qualitative analyses (Harshvardhan and Jha, 2013; Sudhakar *et al*., 2008).

Quantitative analysis of the ability of marine bacterial isolates to degrade LDPE film

The ability of marine bacterial isolates to degrade LDPE film was analyzed quantitatively based on the weight loss (%W) of the LDPE film after the biodegradation process calculated using Eq. 1 (Khandare *et al*., 2022).

$$\text{Weight loss (\%)} = [(Iw - fw) \div Iw] \times 100 \qquad (1)$$

where:

Iw = Initial weight of LDPE film before the degradation process

Fw = Final weight of LDPE film after degradation

Qualitative analysis of the ability of marine bacterial isolates to degrade LDPE film

During the degradation process, marine bacterial isolates form biofilms on the surface of the LDPE film, resulting in changes in its physical and chemical structures. In this study, the qualitative analysis of LDPE plastic degradation by marine bacterial isolates with the identification of LDPE plastic functional groups applied the FTIR method. The frequency range of the spectrum was observed at a wavelength per centimeter of 4000/cm–500/cm (Deswati *et al*., 2023a; Deswati *et al*., 2023b; Khandare *et al*., 2022). After the biodegradation process, a qualitative analysis of the morphology of the LDPE plastic surface was carried out by coating the LDPE film with a thin layer of gold nanoparticles. SEM was employed to observe the physical structure of the samples in the form of holes or cracks due to bacterial activity on the surface of the LDPE film (Jayan *et al*., 2023).

Molecular identification of marine bacterial isolates by analyzing the 16S rRNA gene sequence

Isolation of genomic deoxyribonucleic acid (gDNA) utilized the GeneJET Genomic DNA Purification Kit (ThermoFisher Scientific, USA), while gene amplification used a Polymerase Chain Reaction (PCR) machine (Biometra, Germany), KOD One™ PCR Master Mix -Blue-, and a primer pair of 16S rRNA_27F (5’AGA GTTTGATCMTGGCTCAG3’) and 16S rRNA_1525R (5’AAGGAGGTGWTC CARCC3’) at 35 cycles of PCR (Samimi and Shahriari-Moghadam, 2021). The PCR products were analyzed by 1% agarose gel electrophoresis using GeneRuler 1 kilobase (kb) DNA Ladder (ThermoFisher Scientific, USA). After that, the PCR products were purified, and gene sequencing was performed by a sequencing service provider (1st Base, Singapore) using the Sanger method. Then, the sequencing result in the form of a chromatogram was edited and contigged using the SeqMan™ application. The 16S rRNA gene sequence of each bacterium was BLASTed at the NCBI website (Zhang *et al*., 2000). A total of 15 BLAST sequence data were taken for alignment using the Clustal W algorithm, phylogenetic tree construction using the Neighbor-joining method, determination of evolutionary distance analyzed using the Kimura 2-parameter method, and determination of genetic distance using the MEGA X program. Furthermore, genetic distances were analyzed using the Pairwise Distances method (Kimura, 1980; Kumar *et al*., 2018; Saitou and Nei, 1987) and the bootstrap value used was 1000 (Felsenstein, 1985).

RESULTS AND DISCUSSION

Isolation of plastic-degrading microorganisms

The results of isolation and purification found four marine bacterial isolates that grew in media containing LDPE powder as a selection factor (selective media). Only specific bacterial isolates can live, move, and adapt naturally in the selective medium by producing certain enzymes to use the selective medium as a source of energy (Febria *et al*., 2023; Qubra *et al*., 2023). Four bacterial isolates can produce various enzymes to break down the complex bonds of LDPE and use them as a single carbon source to support the life of microorganisms (Delacuvellerie *et al*., 2019; Jayan *et al*., 2023). Some isolates may include hydrolase, alkane monooxygenase, rubedoxin reductase, and other enzymes (Roager and Sonnenschein, 2019).

Biodegradation of LDPE film by marine bacterial isolates

The result of the LDPE biodegradation process using the four marine bacterial isolates showed that all bacterial isolates grew in Bushnell Haas media containing LDPE film, appearing rather cloudy. In contrast, the control (before the addition of bacterial inoculum) remained clear. This proves that the bacterial isolates can utilize LDPE as the only carbon source. The degradation ability of the four bacterial isolates was quantitatively analyzed based on the weight loss percentage of the LDPE film; the average weight loss of the LDPE film reached 3.4-3.6 milligrams (mg) or about 10-15% during 35 days of incubation, with a daily weight loss rate of 0.004 mg/day. Of the four bacterial isolates, IBP-3 and IBP-4 quantitatively have the best ability, with a maximum weight loss of 15% (Fig. 3). Conversely, the control showed no weight loss.

The weight loss is caused by a degradation process by bacterial isolates which enzymatically break the bonds of the LDPE film and use it as a sole carbon source. LDPE bond-breaking enzymes include laccase, lipase, and esterase (Jayan *et al*., 2023; Khandare *et al*., 2022). The best order of isolate ability in degrading LDPE film is IBP-3>IBP-4>IBP-1>IBP-2. Table 1 shows a comparison of the ability of bacterial isolates to degrade LDPE plastic based on the weight loss percentage of the LDPE film.

In this study, the four marine bacterial isolates showed good weight loss at 35 days (5 weeks) of incubation, compared to the results of several previous studies (Table 1). While this result is the best discovery of this study, further studies are needed to obtain the maximum W% and incubation time of the four bacterial isolates in the LDPE degradation process. The four bacterial isolates have great

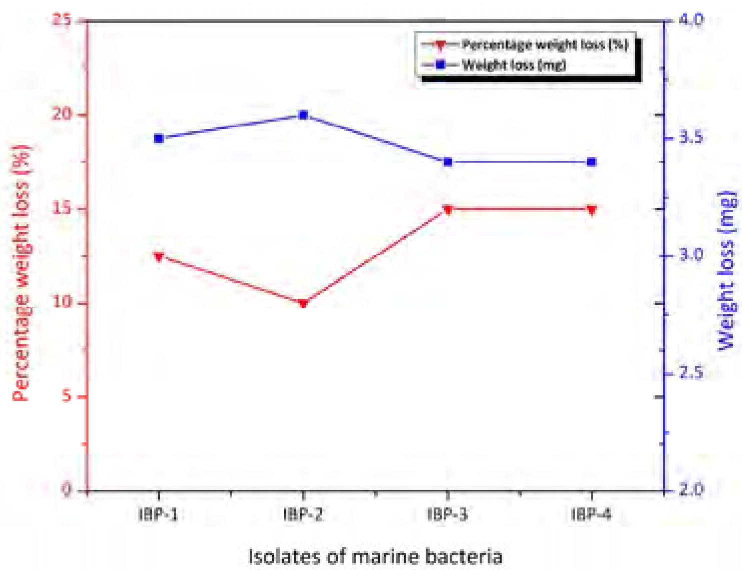


Fig. 3: Weight loss percentage of LDPE film degraded by marine bacterial isolates after biodegradation process for 35 days

Table 1: Comparison of the ability of bacterial isolates to degrade LDPE plastic based on weight loss percentage

Isolates	Sources	Plastic type and size	Weight loss (%)	Day	Sources
Kocuria palustris M16, *Bacillus pumilus* M27 *Bacillus subtilis* H1584	Sea water samples	LDPE	1 1.5 1.75	30	Harshvardhan and Jha, 2013
Bacillus amyloliquefaciens (BSM-1) *Bacillus amyloliquefaciens* (BSM-2)	Municipal solid soil	LDPE 1.5x1.5cm	11 16	60	Das and Kumar, 2015
Stenotrophomonas sp., *Serratia* sp., and *Pseudomonas* sp.	Solid waste-dumping sites	LDPE 10 mg	32 40 21	150	Nadeem *et al.*, 2021
SARR1 bacteria	Soil	LDPE 3×3 cm	38.3	30	Rani *et al.*, 2021
Bacillus cereus	Mangrove sediment	PE PET PS	1.6 6.6 7.4	40	Auta *et al.*, 2017
Bacillus sp. strain 27 *Rhodococcus* sp. strain 36	Mangrove sediment Mangrove sediment	PP	4.0 6.4	40	Auta *et al.*, 2018
Alcanivorax borkumensis	Marine	LDPE 1.5 x 1.2 cm	3.5	80	Delacuvellerie *et al.*, 2019
Bacillus sp.	Marine	LDPE 1x1 cm	1.26	75	Kumari *et al.*, 2019
Isolate IBP-1 Isolate IBP-2 Isolate IBP-3 Isolate IBP-4	Marine plastic waste	LDPE 1 x 1 cm	12.5 10 15 15	35	The current study

potential as a biodegradation agent in reducing LDPE plastic waste.

Qualitative analysis of the ability of marine bacterial isolates to degrade LDPE film

The ability of the isolates to degrade LDPE plastic was confirmed through qualitative analysis of the physical and morphological changes that occurred on the surface of LDPE plastic, which were visualized using high-resolution SEM (Fig. 4).

SEM analysis aims to determine the morphology of the sample's surface (Putra *et al*., 2022). As seen in Fig. 4, there are morphological changes on the surface of LDPE plastic before and after degradation

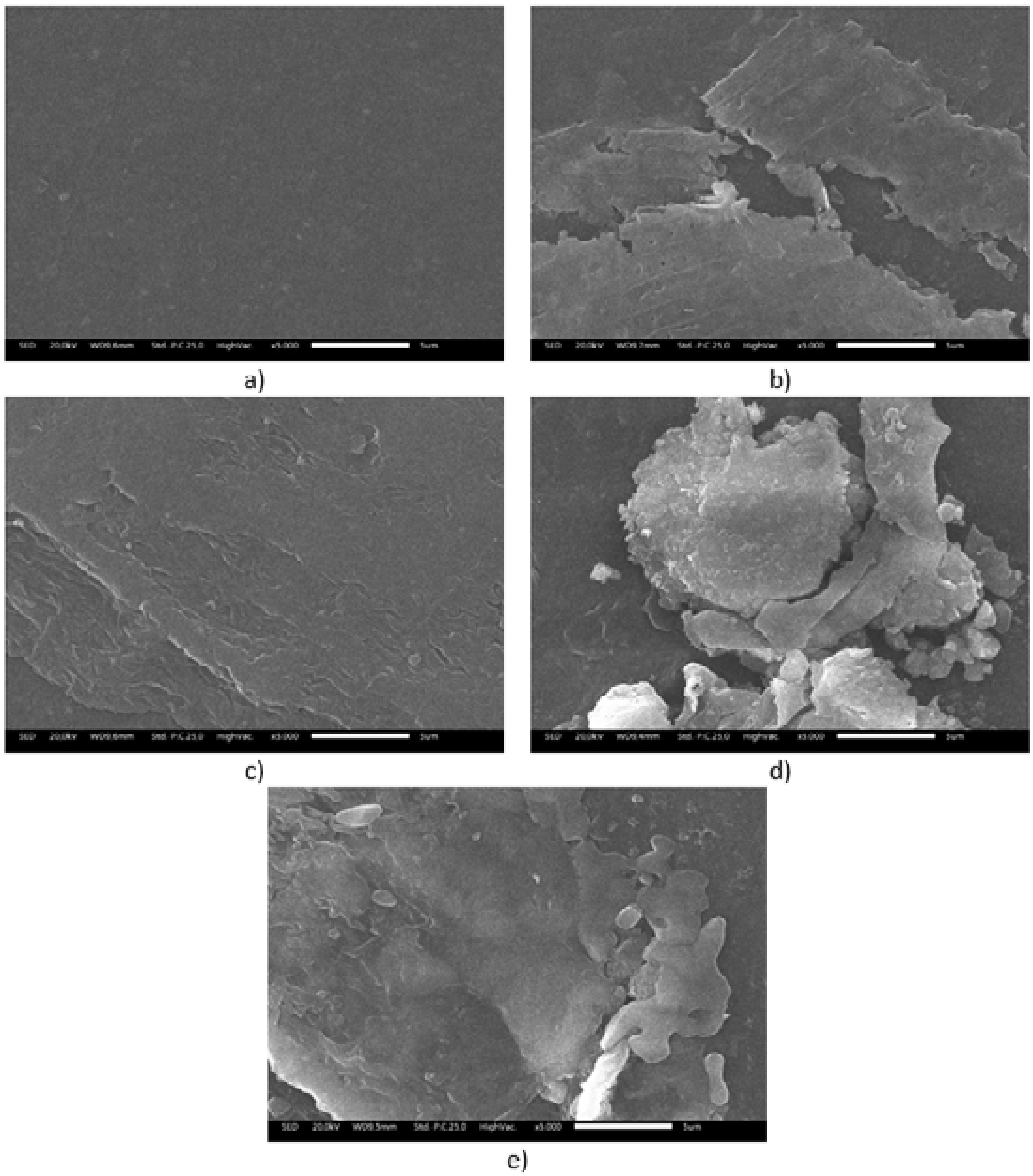


Fig. 4: SEM morphology image of LDPE plastic biodegradation: a) Control (before biodegradation), b) IBP-1, c) IBP-2, d) IBP-3, and e) IBP-4 (after biodegradation)

Fig. 5: EDX spectra of LDPE plastic biodegradation: a) Control (before biodegradation), b) IBP-1, c) IBP-2, d) IBP-3, and e) IBP-4 (after biodegradation)

by bacteria. Before degradation, the LDPE plastic has a smooth surface (Fig. 4a). However, after exposure to bacteria, damages and irregularities occur on the surface, indicating a biodegradation process by enzymes. Variations in the degradation results from different types of bacteria can be observed in the resulting images. As presented in Fig. 4b, the polymers that make up the LDPE plastic break into fragments. Fig. 4c displays the rough and pitted surface of LDPE plastic, while Fig. 4d shows the LDPE polymer breakdown into large clumps. Lastly, Fig. 4e shows the evenly distributed clumps on the surface

Table 2: Changes in the wavenumbers of LDPE plastic biodegradation

Wavenumber (/cm)					
Control	IBP-1	IBP-2	IBP-3	IBP-4	Bonding
3835.31	3836.35	3836.85	3836.31	3852.59	C-H
3740.41	3742.98	3742.07	3743.75	3743.52	C-H
3615.35	3616.54	3616.66	3617.2	3615.69	C-H
2914.7	-	2914.69	2914.58	2914.26	C-H
2849.03	2849.05	2849.13	2849	2848.8	C-H
2305.7	2308.9	2305.9	2306.68	2301.12	C=C
2032.01	-	2028.62	2038.98	2028.69	C=C
1972	1976.79	1976.37	1973.02	1972.46	C-H
1641.42	1700.07	1699.01	1660.49	1645.29	C=C
1463.89	1463.97	1463.96	1463.62	1463.41	C-H
1367.94	1369.04	1368.62	1369.68	1370.72	C-H
1049.38	1052.68	1052.44	1052.9	1048.75	C-O
717.62	717.04	717.41	717.6	717.05	C-H
645.28	642.78	645.19	-	-	C-H

of LDPE plastic. Similar findings have been reported in several prior studies (Asiandu *et al*., 2020; Gan and Zhang, 2019; Kim *et al*., 2021; Urbanek *et al*., 2018).

Energy Dispersive X-ray (EDX) spectroscopy is an analytical technique that uses SEM to analyze the elemental composition of observed samples. Based on study data and EDX spectra in Fig. 5, the final result of the LDPE plastic degradation process shows a decrease in %W from 98.51% (Control) to 98.23% (Fig. 5d). This proves that the biodegradation process converts the LDPE plastic polymer into smaller fragments which are eventually oxidized to CO_2 and H_2O. These smaller fragments have a lighter mass than the original plastic polymer, thus causing a decrease in plastic mass (Amobonye *et al*., 2021; Sarkhel *et al*., 2020). Based on existing data, the optimality of several types of bacteria used can be sorted as follows: IBP-3>IBP-4>IBP-1>IBP-2. Of the four bacterial isolates, IBP-4 can degrade LDPE plastic more optimally, as seen in Figs. 4 and 5.

FTIR is used to identify a compound based on the wavenumber of the pure compound from its functional groups (Deswati *et al*., 2023c; Syamsu *et al*., 2024; Samimi, 2024). Fig. 6 shows that the samples degraded by potential bacterial isolates for five weeks experience visible changes in the spectrum, wavenumbers, and transmittance compared to LDPE before degradation. This signifies changes in chemical bonds or functional groups in LDPE plastic due to interactions with bacteria or degradation products (Khandare *et al*., 2021; Abraham *et al*., 2016; Rajandas *et al*., 2012), among which are wavenumbers 835.31-3615.35/cm, 2849.03/cm, 1972/cm, 1463.89/cm, 1367.94/cm (C-H), 1049.38/cm (C-O), and 2032.01/cm, 1641.42/cm (C=C). The changes in the wavenumbers of LDPE plastic biodegradation are displayed in Table 2. According to Webb *et al*., (2013), microorganisms that degrade plastic waste convert carbon in polymer chains into carbon dioxide or incorporate it into biomolecules. The biodegradation process causes plastic waste to become brittle and break down into smaller fragments until the polymer chains in the plastic waste have a molecular weight low enough to be metabolized by microorganisms. This aligns with the EDX analysis data in Fig. 5, where the W% of the control (before degradation) decreases, compared to W% after degradation. In addition, the samples also experience deletion or loss of frequencies. For example, the missing frequency in LDPE plastic is the wavenumber 2032.01/cm, a type of C-H rock vibration from the C=C bond. All missing chemical bonds contain carbon, nitrogen, hydrogen, and oxygen compounds. This is in line with a statement by Yuan *et al*. (2020) that the reduction or addition of hydroxyl groups indicates that monooxygenase enzyme activity has occurred. Nevertheless, initiating polymer chain cleavage is the longest and most challenging step in the degradation process. Thus, a long incubation time is required to produce enough carbonyl groups (C=O) to proceed with the degradation process.

Mechanism of plastic biodegradation

Bacteria can degrade LDPE plastic through biodegradation. In this regard, LDPE is utilized by bacteria as a source of carbon and energy. Based on study data and characterization, the main stages of the LDPE plastic biodegradation process by bacteria are as follows: 1) Bacterial attachment: bacterial isolates attach to the surface of LDPE plastic (Fig. 6); 2) Extracellular enzyme development: bacterial isolates produce extracellular enzymes that attach to the LDPE plastic polymer (Fig. 7); 3) LDPE polymer breakdown: the extracellular enzymes create smaller fragments of LDPE plastic (Fig 4); 4) Carbon oxidation: the smaller fragments are oxidized to carbon dioxide (CO_2) and water (H_2O); and 5) Plastic weight reduction: the biodegradation process of LDPE plastic leads to a reduction in plastic weight, which can be observed through a decrease in mass loss percentage (Fig. 3) (Ali *et al*., 2021; Amobonye *et al*., 2021; Asiandu *et al*., 2020).

Identification of marine bacterial isolates based on 16S rRNA gene sequence analysis

The identification results of the four marine bacterial isolates based on 16S rRNA gene sequence analysis (Samimi and Shahriari Moghadam, 2020) and phylogenetic tree analysis can be seen in Fig. 8.

The position of Isolate IBP-1 in cluster B of the phylogenetic tree is adjacent to *Lysinibacillus* sp. WTXJ1-4 (KP150574.1). Isolate IBP-2 is adjacent to *Bacillus* sp. VZ1M (JQ618102.1). Isolate IBP-4 is adjacent to *Bacillus paramycoides* strain Alaa5 (OM984660.1), while Isolate IBP5 is adjacent to *Bacillus cereus strain* fg33 (ON715736.1). Based

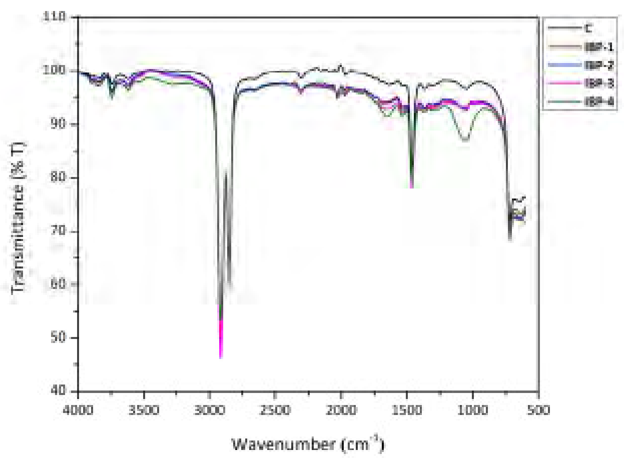


Fig. 6: FTIR spectra of LDPE plastic biodegradation: a) Control (before biodegradation), b) IBP-1, c) IBP-2, d) IBP-3, and e) IBP-4 (after biodegradation)

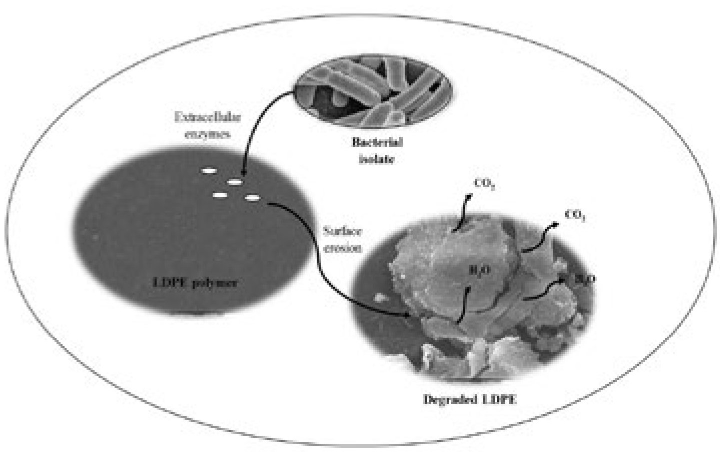


Fig. 7: Biodegradation mechanism of LDPE plastic by bacteria

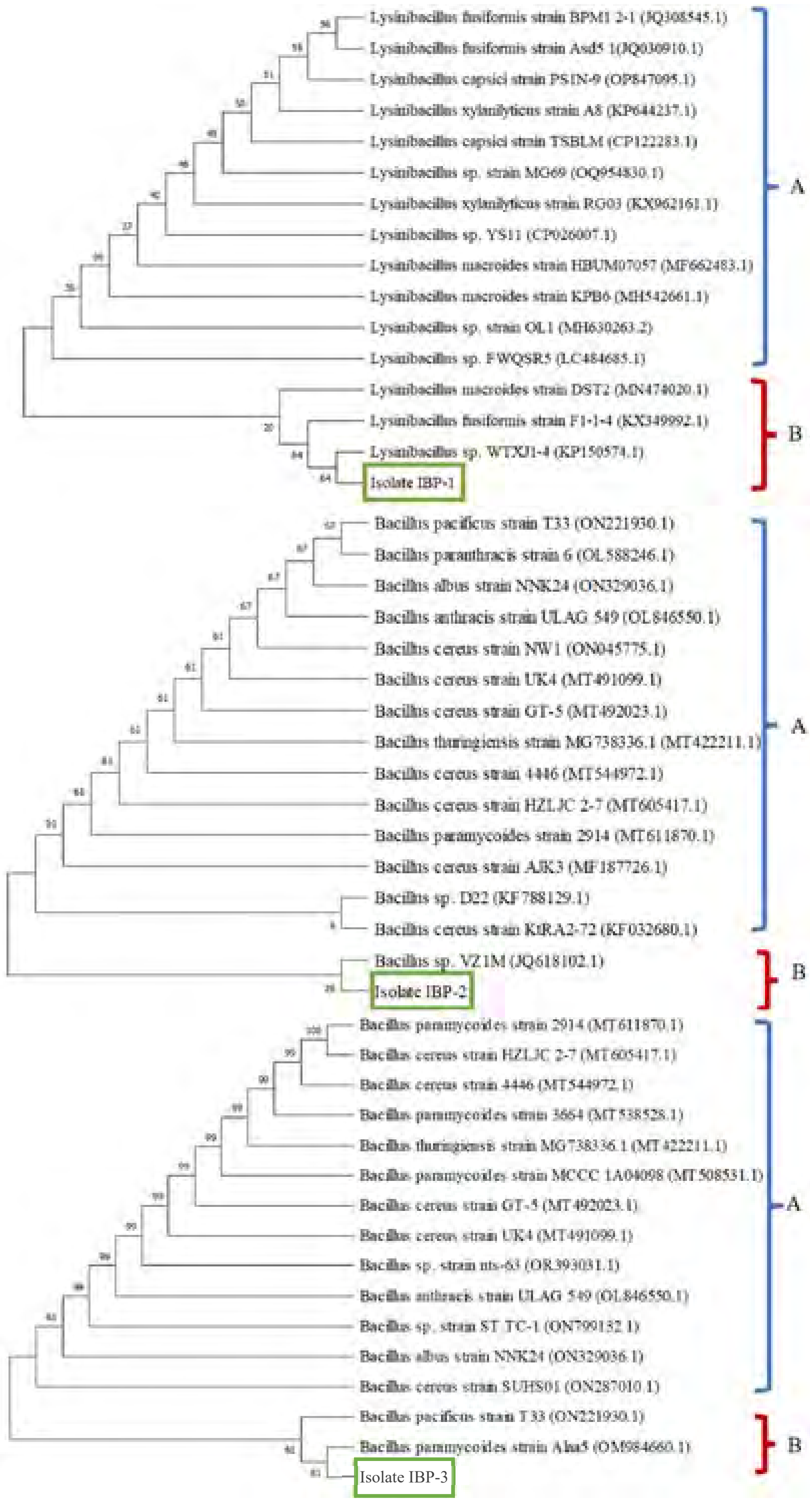
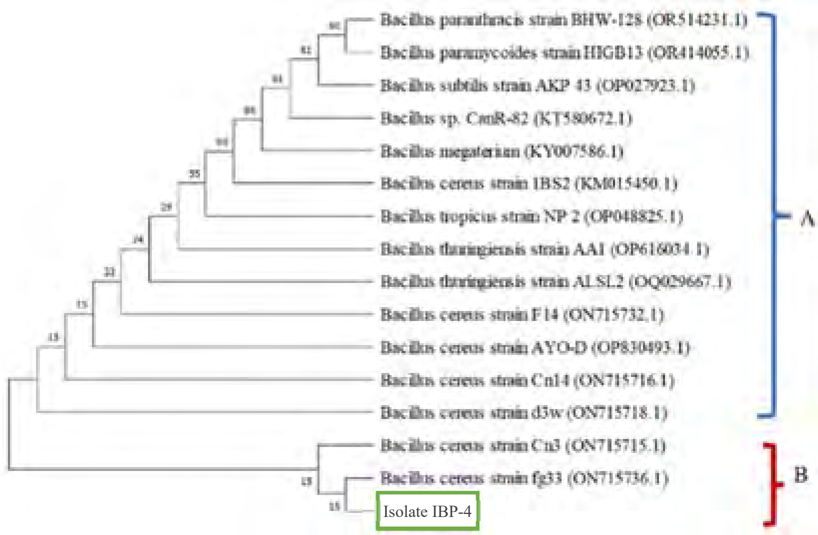


Fig. 8: Identification of LDPE-degrading marine bacteria based on 16S rRNA gene sequence analysis and phylogenetic tree analysis using the Neighbor-joining method with a bootstrap value of 1000 replicates



Continued Fig. 8: Identification of LDPE-degrading marine bacteria based on 16S rRNA gene sequence analysis and phylogenetic tree analysis using the Neighbor-joining method with a bootstrap value of 1000 replicates

on the results of BLAST analysis, genetic distance calculation, and phylogenetic tree construction, the four bacterial isolates are identified as *Lysinibacillus* sp. IBP-1, *Bacillus* sp. IBP-2, *Bacillus paramycoides* IBP-3, and *Bacillus cereus* IBP-4.

CONCLUSIONS

Four bacterial isolates are found from isolated marine plastic debris; they grow in media containing LDPE powder as the sole carbon source. These bacteria have the potential to degrade LDPE. Based on the quantitative study using the weighing process and EDX analysis, the four bacterial isolates showed the best ability to degrade LDPE plastic compared to the results of several previous studies. From the quantitative analysis of the biodegradation test during five weeks of incubation, the four isolates were found to experience a weight loss of 3.4-3.6 mg or about 10-15%, with a daily weight loss rate of 0.004 mg/day. EDX data also showed a decrease in LDPE mass from 98.51% (Control) to 98.23%. This proves that biodegradation has converted the LDPE plastic polymer into smaller fragments which are eventually oxidized to CO_2 and H_2O. Additionally, a qualitative analysis was conducted comprehensively using SEM and FTIR. Changes in the morphology and structure of the plastic surface after degradation were visualized using high-resolution SEM. The surface of the LDPE film was smooth and flat before the degradation process (control). After the biodegradation process by the four bacteria, damages occurred to the LDPE film as follows: the LDPE film broke into several parts (IBP-1), the surface of the LDPE film became rough and pitted (IBP-2), the LDPE film decomposed into large clumps (IBP-3), and evenly-distributed clumps formed on the surface of the LDPE film (IBP-4). Furthermore, the results of the FTIR analysis revealed a change in the wavenumber frequency. Changes in morphology, surface structure, and wavenumbers indicate the activity and performance of bacterial extracellular enzymes in degrading LDPE. Overall, the results of the quantitative and qualitative analyses are interrelated in explaining the biodegradation process of LDPE film by bacteria. Based on both analyses, the four bacterial isolates found in this study are found to be potential LDPE plastic degraders. From the identification, three of the four bacterial isolates were >90% identified as *Lysinibacillus* sp. IBP-1, *Bacillus paramycoides* IBP-3, and *Bacillus cereus* IBP-4, whereas IBP-2 showed a percent identity of only 78.56-83.85% (<90%). This also signifies that IBP-2 is a new strain and species in the genus *Bacillus*. In this study, the four isolates showed the discovery of new strains with the best order of ability to degrade LDPE film polymer (IBP-3>IBP-4>IBP-1>IBP-2). The results of this study can be further developed as an alternative method for LDPE plastic degradation to reduce plastic waste pollution in the future. Therefore, future studies are highly recommended to involve single isolates and consortia, optimization of the number of bacterial inoculums and environmental factors (incubation time, salinity, and other factors), and examination of the degradation mechanism and enzymes involved in the LDPE degradation process.

AUTHOR CONTRIBUTIONS

F.A. Febria, the corresponding author, conducted literature review, designed and carried out experiments, analyzed and interpreted data, prepared the manuscript, and edited the manuscript. A. Syafrita was responsible for the sampling, experiments, and data collection. A. Putra conducted data analysis, interpreted the results, and prepared the discussion and conclusion sections of the manuscript. H. Hidayat performed secondary data collection, carried out supporting analysis, linked the findings with existing literature, interpreted data, and arranged the layout of the manuscript. C. Febrion assisted in drafting, reviewing, and revising the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. Ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS	DEFINITION
%	Percentage
°C	Degree Celsius
AFM	Atomic force microscopy
ATR-FTIR	Attenuated Total Reflectance-Fourier Transform Infra-Red Spectroscopy
Bacillus cereus NJD 1	NJD 1 strain code bacteria *Bacillus cereus*
Bacillus subtilis H-248	H-248 strain code bacteria *Marinobacter* sp
Bacillus subtilis H-248	H-248 strain code bacteria *Marinobacter* sp
BLAST	Basic local alignment search tool
$CaCl_2.2H_2O$	Calcium chloride dihydrate
cfu/mL	Colony form unit per milliliter
cm	Centimeter
CO_2	Carbon dioxide
DNA	Deoxyribonucleic Acid
EDX	Energy dispersive x-ray spectroscopy
FTIR	Fourier Transform Infra-Red
fw	Final weight
g/L	Gram per liter
GCMS	Gas chromatography-mass spectrometry
H_2O	Dihydrogen oxide

IBP-1	Plastic bacterial isolate code 1
IBP-2	Plastic bacterial isolate code 2
IBP-3	Plastic bacterial isolate code 3
IBP-4	Plastic bacterial isolate code 4
IKTF-KP	*Direktur Jenderal Industri Kimia, Farmasi, dan Tekstil (IKFT) Kementerian Perindustrian (IKFT-KP)* (Director General of Chemical, Pharmaceutical, and Textile Industries, Ministry of Industry of Indonesia)
Iw	Initial weight
K_2HPO_4	Dipotassium phosphate
Kb	Kilobase pair
KCl	Potassium chloride
kg/capita/y	Kilogram per capita per year
LDPE	Low-density polyethylene
Marinobacter sp H-244	H-244 strain code bacteria *Marinobacter* sp
mg/L	Milligram per liter
$MgSO_4.7H_2O$	Magnesium sulfate heptahydrate
mL	Milliliter
mt/y	Million tons per year
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NCBI	National center for biotechnology information
NH_4NO_3	Ammonium nitrate
PCR	Polymerase Chain Reaction
rpm	Rotations per minute
SDS	Sodium dodecyl sulfate
SEM	Scanning electron microscope
SIPSN KLHK	*Sistem Informasi Pengelolaan Sampah Nasional Kementerian Lingkungan Hidup dan Kehutanan* (National Waste Management Information System, Ministry of Environment and Forestry of Indonesia)
W%	Weight loss percentage

REFERENCES

Abraham, J.; Ghosh, E.; Mukherjee, P.; Gajendiran, A., (2016). Microbial degradation of low density polyethylene. Environ. Prog. Sustainable Energy. 33(3): 676–680 **(5 pages).**

Ali, S.S.; Elsamahy, T.; Al-Tohamy, R.; Zhu,D.; Mahmoud, Y.A.G.; Koutra, E.; Metwally, M.A.; Kornaros, M.; Sun, J., (2021). Plastic wastes biodegradation: Mechanisms, challenges and future prospects. Sci. Total Environ. 780: 146590 **(18 pages)**.

Amobonye, A.; Bhagwat, P.; Singh, S.; Pillai, S., (2021). Plastic Biodegradation: Frontline microbes and their enzymes. Sci. Total Environ.: 759: 143536 **(56 Pages).**

Asiandu, A.P.; Wahyudi, A.; Sari, S.W., (2020). A Review: Plastics Waste Biodegradation Using Plastics-Degrading Bacteria. J. Environ. Treat. Technol., 9(1): 148–157 **(10 pages)**.

Auta, H.S.; Emenike, C.U.; Fauziah, S.H. (2017). Screening of Bacillus strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation. Environ. Pollut., 231: 1552–1559 **(8 pages)**.

Auta, H.S.; Emenike, C.U.; Jayanthi, B.; Fauziah, S.H., (2018). Growth kinetics and biodeterioration of polypropylene microplastics by Bacillus sp. and Rhodococcus sp. isolated from mangrove sediment. Mar. Pollut. Bull., 127: 15–21 **(7 pages)**.

Cheng, K.; Hao, W.; Wang, Y.; Yi, P.; Zhang, J.; Ji, W., (2020). Understanding the emission pattern and source contribution of hazardous air pollutants from open burning of municipal solid waste in China. Environ. Pollut., 263: 114417 **(9 pages)**.

Danso, D.; Chow, J.; Streita, W.R., (2019). Plastics: Environmental and biotechnological perspectives on microbial degradation. Appl. Environ. Microbiol., 85(19) **(14 pages)**.

Das, M.P.; Kumar, S., (2015). An approach to low-density polyethylene biodegradation by Bacillus amyloliquefaciens. 3 Biotech., 5(1): 81–86 **(6 pages)**.

Delacuvellerie, A.; Cyriaque, V.; Gobert, S.; Benali, S.; Wattiez, R., (2019). The plastisphere in marine ecosystem hosts potential specific microbial degraders including Alcanivorax borkumensis as a key player for the low-density polyethylene degradation. J. Hazard. Mater., 380(2018): 120899 **(11 pages)**.

Deswati, D.; Kurnia Hamzani, B.; Yusuf, Y.; Fitri, W.E; Putra, A., (2023a). Detection of microplastic contamination in table salts in Padang City, Indonesia, and control strategies for choosing healthy salt. Int. J. Environ. Anal. Chem., 1–16 **(16 pages)**.

Deswati, D.; Tetra, O.N.; Febriani, U.; Suparno, S.; Pardi, H.; Putra, A., (2023b). Detection of microplastic in sediments at beach tourism area of Muaro Lasak, Padang City, West Sumatra, Indonesia. AACL Bioflux., 16(5): 2765–2780 **(6 pages)**.

Deswati, D.; Tetra, O.N.; Hayati, M.; Putra, A.; Fitri, W.E.; Suparno, S.; Pardi, H., (2023c). Preliminary detection of microplastics in surface water of Maninjau Lake in Agam, Indonesia. AACL Bioflux., 16(5): 2601–2614 **(14 pages)**.

Febria, F.A.; Zulkhairiah, F.; Walpajri, F.; Putra, A.; Syukriani, L., (2023). Biofilm-forming heavy metal resistance bacteria from Bungus Ocean fisheries port (PPS) West Sumatra as a waters bioremediation agent. Pakistan J. Biol. Sci., 26(4): 168–173 **(9 pages)**.

Felsenstein, J., (1987). Confidence limits on phylogenies: An approach using the bootstrap. Evolution., 39: 783-791 **(9 pages).**

Gan, Z.; Zhang, H., (2019). PMBD: A comprehensive plastics microbial biodegradation database. Database (Oxford). 2019: 1–11 **(11 pages)**.

Gangwar, C.; Choudhari, R.; Chauhan, A.; Kumar, A.; Singh, A.; Tripathi, A., (2019). Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. Environ. Int., 125: 191–199 **(9 pages)**.

Geyer, R.; Jambeck, J.R.; Law, K.L., (2017). Production, use, and fate of all plastics ever made. Sci. Adv., 3:e1700782 **(5 pages)**.

Gupta, K.K.; Devi, D., (2019). Biodegradation of low density polyethylene by selected bacillus sp. Gazi Univ. J. Sci., 32(3): 802–813 **(12 pages)**.

Gupta, K.K.; Devi, D., (2020). Biofilm mediated degradation of commercially available LDPE films by bacterial strains isolated from partially degraded plastic. Remediation. 30(4): 39–47 **(9 pages)**.

Harshvardhan, K.; Jha, B., (2013). Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India. Mar. Pollut. Bull., 77(1–2): 100–106 **(7 pages)**.

IKFT-KP., (2019.) Director General of Chemical, Pharmaceutical, and Textile Industries Ministry of Industry of Indonesia. [In Indonesia].

Jayan, N.; Skariyachan, S.; Sebastian, D., (2023). The escalated potential of the novel isolate Bacillus cereus NJD1 for effective biodegradation of LDPE films without pre-treatment. J. Hazard. Mater., 455: 131623 **(13 pages)**.

Khandare, S.D.; Agrawal, D.; Mehru, N.; Chaudhary, D.R., (2022). Marine bacterial based enzymatic degradation of low-density polyethylene (LDPE) plastic. J. Environ. Chem. Eng., 10(3): 107437 **(15 pages)**.

Khandare, S.D.; Chaudhary, D.R.; Jha, B., (2021). Marine bacterial biodegradation of low-density polyethylene (LDPE) plastic. Biodegradation. 32(2): 127–143 **(17 pages)**.

Kim, H.W.; Jo, J.H.; Kim, Y. Bin; Le, T.K.; Cho, C.W.; Yun, C.H.; Chi, W.S.; Yeom, S.J., (2021). Biodegradation of polystyrene by bacteria from the soil in common environments. J. Hazard. Mater., 416(May): 126239 **(9 pages).**

Kimura, M., (1980). A simple method for estimating evolutionary rates of base substitutions through comparative studies of nucleotide sequences. J. Mol. Evol., 16(2): 111–120 **(10 pages).**

Kumar, S.; Stecher, G.; Li, M.; Knyaz, C.; Tamura, K., (2018). MEGA X: Molecular evolutionary genetics analysis across computing platforms. Mol. Biol. Evol., 35(6): 1547–1549 **(3 pages)**.

Kumari, A.; Chaudhary, D.R.; Jha, B., (2019). Destabilization of polyethylene and polyvinylchloride structure by marine bacterial strain. Environ. Sci. Pollut. Res., 26(2): 1507–1516 **(10 pages)**.

Li, Z.; Wei, R.; Gao, M.; Ren, Y.; Yu, B.; Nie, K.; Xu, H.; Liu, L., (2020). Biodegradation of low-density polyethylene by Microbulbifer hydrolyticus IRE-31. J. Environ. Manage., 263: 110402 **(8 pages)**.

Nadeem, H.; Alia, K.B.; Muneer, F.; Rasul, I.; Siddique, M.H.; Azeem, F.; Zubair, M., (2021). Isolation and identification of low-density polyethylene degrading novel bacterial strains. Arch. Microbiol., 203(9): 5417–5423 **(7 pages)**.

Pinto, M.; Zhao, Z.; Klun, K.; Libowitzky, E.; Herndl, G.J., (2022). Microbial Consortiums of Putative Degraders of Low-Density Polyethylene-Associated Compounds in the Ocean. MSystems., 7(2) **(24 pages)**.

Putra, A.; Fauzia, S.; Deswati; Arief, S.; Zein, R., (2022). Preparation, characterization, and adsorption performance of activated rice straw as a bioadsorbent for Cr(VI) removal from aqueous solution using a batch method. Desalin. Water Treat., 264(July): 121–132 **(13 pages)**.

Qubra, T.; Febria F.A.; Djamaan, A., (2023). Isolation and characterization of polystyrene-starch polymer degrading bacteria coating of slow-release urea fertilizer. IOSR J. Biotechnol. Biochem., 9(2):1-6 **(6 pages)**.

Raddadi, N.; Fava, F., (2019). Biodegradation of oil-based plastics in the environment: Existing knowledge and needs of research and innovation. Sci. Total Environ., 679: 148–158 **(11 pages)**.

Rajandas, H.; Parimannan, S.; Sathasivam, K.; Ravichandran, M.; Yin, L.S., (2012). A novel FTIR-ATR spectroscopy based technique for the estimation of low-density polyethylene biodegradation. Polym. Test., 31(8): 1094–1099 **(6 pages)**.

Rani, R.; Jitender; Singh, N.P.; Santal, A.R., (2021). Isolation, characterization and optimization of bacterial isolate SARR1 for biodegradation of pretreated low density polyethylene. J. Appl. Nat. Sci., 13(2): 561–570 **(10 pages).**

Roager, L.; Sonnenschein, E.C., (2019). Bacterial Candidates for Colonization and Degradation of Marine Plastic Debris. Environ. Sci. Technol., 53(20): 11636–11643 **(8 pages)**.

Roohi, K.; Bano, K.; Kuddus, M.; Zaheer, M.R.; Zia, Q.; Khan, F.M.; Gupta, A.; Aliev, G., (2017). Microbial enzymatic degradation of biodegradable plastics, Curr. Pharm. Biotechnol., 18: 429–440 **(9 pages).**

Samimi, M., (2024). Efficient biosorption of cadmium by Eucalyptus globulus fruit biomass using process parameters optimization. Global J. Environ. Sci. Manage., 10(1): 27-38 **(12 pages).**

Samimi, M.; Shahriari Moghadam, M., (2020). Phenol biodegradation by bacterial strain O-CH1 isolated from seashore. Global J. Environ. Sci. Manage., 6(1): 109-118 **(10 pages).**

Samimi, M.; Shahriari-Moghadam, M., (2021). Isolation and identification of Delftia lacustris Strain-MS3 as a novel and efficient adsorbent for lead biosorption: Kinetics and thermodynamic studies, optimization of operating variables. Biochem. Eng. J., 173: 108091 **(9 pages).**

Sangeetha Devi, R.; Ramya, R.; Kannan, K.; Robert Antony, A.; Rajesh Kannan, V., (2019). Investigation of biodegradation potentials of high density polyethylene degrading marine bacteria isolated from the coastal regions of Tamil Nadu, India. Mar. Pollut. Bull., 138(July 2018): 549–560 **(12 pages)**.

Saitou, N.; Nei, M., (1987). The neighbor-joining method: a new method for reconstructing phylogenetic trees. Mol. Biol. Evol., 4(4): 406–425 **(20 pages)**.

Sarkhel, R.; Sengupta, S.; Das, P.; Bhowal, A., (2020). Comparative biodegradation study of polymer from plastic bottle waste using novel isolated bacteria and fungi from marine source. J. Polym. Res., 27(1): 1–8 **(8 pages)**.

Sekhar, V.C.; Nampoothiri, K.M.; Mohan, A.J.; Nair, N.R.; Bhaskar, T.; Pandey, A., (2016). Microbial degradation of high impact polystyrene (HIPS), an e-plastic with decabromodiphenyl oxide and antimony trioxide. J. Hazard. Mater., 318: 347–354 **(25 pages)**.

SIPSN KLHK, (2023). National waste generation and waste composition data. [In Indonesia].

Sudhakar, M.; Doble, M.; Murthy, P.S.; Venkatesan, R., (2008). Marine microbe-mediated biodegradation of low- and high-density polyethylenes. Int. Biodeterior. Biodegrad., 61(3): 203–213 **(11 pages).**

Syamsu, D.A.; Deswati, D.; Syafrizayanti, S.; Putra, A.; Suteja, Y., (2024). Presence of microplastics contamination in table salt and estimated exposure in humans. Global J. Environ. Sci. Manage., 10(1): 205–224 **(20 pages)**.

Taghavi, N.; Singhal, N.; Zhuang, W.Q.; Baroutian, S., (2021). Degradation of plastic waste using stimulated and naturally occurring microbial strains. Chemosphere., 263: 127975 **(14 pages).**

Urbanek, A.K.; Rymowicz, W.; Mirończuk, A.M., (2018). Degradation of plastics and plastic-degrading bacteria in cold marine habitats. Appl. Microbiol. Biotechnol., 102(18): 7669–7678 **(10 pages)**.

Varó, I.; Osorio, K.; Estensoro, I.; Naya-Català, F.; Sitjà-Bobadilla, A.; Navarro, J.C.; Pérez-Sánchez, J.; Torreblanca, A.; Piazzon, M.C., (2021). Effect of virgin low density polyethylene microplastic ingestion on intestinal histopathology and microbiota of gilthead sea bream. Aquaculture., 545:737245 **(13 pages).**

Webb, H.K.; Arnott, J.; Crawford, R.J.; Ivanova, E.P., (2013). Plastic degradation and its environmental implications with special reference to Poly(ethylene terephthalate). Polymers (Basel)., 5(1): 1–18 **(18 pages).**

Yuan, Z.; Georgescu, R.; Schauer, G.D.; O'Donnell, M.E.; Li, H., (2020). Structure of the polymerase ε holoenzyme and atomic model of the leading strand replisome. Nat. Commun., 11(1): 1–11 **(11 pages)**.

Yuan, J.; Ma, J.; Sun, Y.; Zhou, T.; Zhao, Y.; Yu, F., (2020). Microbial degradation and other environmental aspects of microplastics/ plastics. Sci. Total Environ., 715: 136968 **(9 pages)**.

Yang, H.; Chen, G.; Wang, J., (2021). Microplastics in the marine environment: Sources, fates, impacts and microbial degradation. Toxics., 9(2): 1–19 **(19 pages)**.

Zhang, Z.; Schwartz, S.; Wagner, L.; Miller, W., (2000). A greedy algorithm for aligning DNA sequences. J. Comput. Biol., 7(1–2): 203–214 **(12 pages)**.

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CASE STUDY

Spatiotemporal analysis of oil palm land clearing

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ABSTRACT

BACKGROUND AND OBJECTIVES: Oil palm is an agricultural crop essential to Indonesia's economy. Therefore, the number of oil palm plantations has increased, leading to widespread deforestation in Indonesia, including Jambi Province. In this investigation, remote sensing with a geographic information system approach is used to evaluate deforestation and the land changes caused by oil palm expansion conducted by smallholders that eventually influence environmental change. This study conducts a spatiotemporal (spatial and temporal) analysis of oil palm land clearing in Jambi Province that results in land changes and environmental impacts.

METHODS: This research used data from Landsat 8 satellite imagery. The land cover classification was conducted using the Maximum Likelihood approach, whereas the overlay method was used for land change analysis. The accuracy assessment of classification results used a confusion matrix by considering the overall accuracy and Kappa Coefficient. Within the field observation, the validation class was the oil palm class, and documentation and plotting using the global positioning system were conducted. Other classes were validated using the region of interest collected through Google Earth. This research used the Aviation Reconnaissance Coverage Geographic Information System 10.1 software to transform the categorization results into vector data.

FINDINGS: This study shows that the land cover classification results have high accuracy and that the area of oil palm land from 2015 to 2019 has increased along with a decrease in land used, such as forests and others. The area of oil palm land in 2014 was 2,071,345 hectares, whereas that in 2019 was 2,110,545 hectares. In particular, the land cover area increased by 39.2 thousand hectares because of land clearing and deforestation. Moreover, the built-up area has increased in the last five years by 165,358 hectares. The number of oil palm plantations in relatively plain areas tends to be greater than that in areas with relatively high altitudes and steep slopes. Small farmers' area of oil palm land has increased by 1,000 hectares from 2014 to 2018. The most remarkable increase of approximately 38,889 hectares has occurred from 2016 to 2017.

CONCLUSION: This study demonstrates that using Landsat 8 imagery with Geographic Information System approaches provides the optimal method for an in-depth analysis of land cover changes related to oil palm expansion and land clearing that occur on a broad spatial and temporal scale in Jambi Province. This study shows that smallholder oil palm plantations in the Jambi region play an important role in increasing deforestation not only in Jambi Province but also throughout Indonesia. This study is expected to serve as a valuable resource for informing policy decisions aimed at addressing the issue of deforestation resulting from the prospective increase in oil palm crops in the forthcoming period.

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52	3	6

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INTRODUCTION

Oil palm is an agricultural crop essential for the Indonesian economy. Oil palm's versatile uses as an essential ingredient for food, cosmetics, and renewable energy have increased the demand for oil palm (Purnomo *et al.*, 2020). Indonesian oil palm production is estimated to have increased by an average of 450,000 hectares (ha) per year from 1995 to 2015 (Ven *et al.*, 2018). Nevertheless, a consistent annual increase of approximately 1 million hectares (Mha) in the quantity of oil palm plantations in Indonesia occurred in 2015 until 2018 (Kementerian Pertanian RI., 2020). Indonesian plantations reached a critical point in 2006 because of the increased productivity fulfillment to meet oil palm needs through expansion driven by local factors, economic profitability, market preferences, and foreign factors (Varkkey *et al.*, 2018). Furthermore, economic and political incentives for oil palm cultivation ultimately drive forest loss and land conversion or changes in land utilization, mainly concentrated in lowland areas, fertile wetlands, and areas of relatively minor forest density (Cisneros *et al.*, 2021). In Indonesia, deforestation is mainly driven by plantation extensification factors. The largest plantation extensification is caused by the extensification of oil palm plantations (Austin *et al.*, 2019). Various policies and regulations have been implemented to raise commitment to deforestation prevention. Nevertheless, in Indonesia, deforestation continues despite regulations and policies, such as nonstate market-driven (NSMD) regulations for agricultural commodities (for example, eco-labels and certification systems) and government policies (Heilmayr *et al.*, 2020). A total of 91 square kilometers (km^2) of forest, 24 km^2 of peat forest, and 23 km^2 of primary forest were lost in certified plantation areas after the certification process started. Indonesia's annual deforestation rate is one of the highest. The yearly deforestation rate for 2000–2015, encompassing all oil palm plantations, was 3.3 percent (%) per annum. Similar temporal dynamics also occur for peat and primary forest deforestation (Carlson *et al.*, 2018). Productivity per hectare on mature, productive land cannot increase through intensification. In this case, an additional 6 million hectares (Mha) of oil palm plantation land is the estimated area needed to meet crude palm oil (CPO) demand in 2025 (Khatiwada *et al.*, 2018). High deforestation rates and the need for land to meet this demand ultimately affect ecosystem services, such as loss of utilization for wood production, habitat loss for endemic species, risen carbon dioxide (CO_2) emissions, and reduced biodiversity (Sharma *et al.*, 2019). High deforestation can also result in indigenous and forest-dependent communities losing access to forest resources and reducing ethnic heterogeneity because of fragmentation from deforestation (Alesina *et al.*, 2019). Rising oil palm production results in intense pressure on land without substantially increasing CPO yields and land protection effectiveness (Schebek *et al.*, 2018). Jambi Province is one of the provinces in western Indonesia with a fast deforestation rate. Approximately 44.6% of land utilized outside forest areas in Jambi Province is abandoned or unproductive. Approximately 96% or more of protected areas (834,800 ha) are maintained according to their function (Rustiadi *et al.*, 2018). Oil palm plantations' rapid expansion will increase oil palm plantations' area by 20% between 2014 and 2040 if companies are committed to meeting the current needs and rising productivity (Afriyanti *et al.*, 2016). Land changes in Jambi Province are also affected by the transmigration program integrated into oil palm plantation development through a partnership program (Yanita *et al.*, 2019). Land acquisition in Jambi generally occurs through forest land utilization and market transactions (Krishna *et al.*, 2017). Land changes occurring in Jambi have resulted in a rise in the earth's surface temperature, flooding frequency in Jambi, and wildlife habitat fragmentation (Sabajo *et al.*, 2017). Remote sensing is an efficient and economical method that offers valuable ecological data to characterize land ecosystems and monitor changes in land cover (Austin *et al.*, 2019). Remote sensing data are useful for land mapping. Spatial features can add spectral information, thereby contributing to mapping complex land cover success (Mahdianpari *et al.*, 2018). Land cover mapping using remote sensing techniques often involves the utilization of image classification methods, which may include object-based image analysis to achieve accurate results. Objects are frequently formed through image segmentation, which involves separating an image into clusters of pixels. The objects are subsequently utilized as a fundamental unit for spatial analysis. A method for accuracy assessment by determining accuracy with objects that have been separated before conducting classification can be utilized (Costa *et al.*, 2018). Parameters can be categorized into pixel-based type, object-based type (such as image segmentation obtained from spatial high-resolution images), and subpixel-based type (fractional images) (Li *et al*., 2019). This study utilizes remote sensing that can see land changes over time by using a Landsat sensor. Landsat 8 is a remote sensing satellite sensor tool that provides images with relatively good spatial but coarse temporal resolution, with medium resolution (Ling *et al*., 2016). Previous studies generally used GIS and remote sensing in oil palm plantation mapping (Rosyidy *et al*., 2023), land cover change that impacts the increase in the surface temperature in urban areas (Suharyanto *et al*., 2023), zoning of malaria distribution related to landcover changes (Payus and Sentian, 2022), zoning of polluted and unpolluted areas (Adimalla and Taloor, 2020), forest expansion (Hashemi, 2018), determining the land change status in a region (Asen *et al*., 2018), and understanding patterns and risks of natural disasters (Matin *et al*., 2017). In previous research, a gap exists regarding efforts to determine land changes based on data comparison over a certain period accompanied by the oil palm land distribution mapping. Thus, the advantages of remote sensing and GIS are also used in the present research to determine the land changes that occurred in 2014–2019 and map the distribution of private and private oil palm lands. The visualization results in the space and time dimensions, and the digital maps help understand the problems of land changes and oil palm development by small farmers. Moreover, these results are visualized in graphical form. In this research, the samples of land change and oil palm development in Jambi Province are used to evaluate deforestation and land changes caused by oil palm expansion carried out by small farmers that eventually influence environmental change. This study was conducted in Jambi, Indonesia, in 2023.

MATERIALS AND METHODS

Jambi Province is situated on the island of Sumatra. The province possesses a total land area of 53,435 km^2. Jambi Province is located between 0 degrees (°) 45 minutes (′) South (S) to 20°45′ S and 101°10′ East (E) to 104°55′ E. The northern boundaries of Jambi Province are shared with Riau Province and Riau Islands. The eastern boundary of the region is next to the South China Sea. The southern boundaries of Jambi Province are shared with the Provinces of South Sumatera, West Sumatera, and Bengkulu. The province comprises 11 districts, including the Districts of Kerinci, Merangin, Sarolangun, and Batanghari, Sungai Penuh City, East Tanjung Jabung, West Tanjung Jabung, Tebo District, Bungo District, Jambi City, and Muaro Jambi (Fig. 1). In 2021, the observation station of the meteorology, climatology, and geophysics agency/Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) Muaro Jambi indicated that the average air temperature in Jambi Province was 27.2 Degrees Celsius (°C), with a minimum temperature of 21.6 °C. The maximum temperature in Jambi Province was close to 34 °C. In Jambi Province, the dry season is short and hot, and the rainy season is usually short and warm. The weather is generally hot, rainy, and cloudy all year round. Jambi Province displays a varied topographical landscape, with altitudes ranging from 0 meters (m) above sea level in the east to over 1,000 m above sea level. As one progresses toward the west, the terrain becomes increasingly elevated, eventually giving way to the hilly and mountainous expanse of the Bukit Barisan Range, which borders the Bengkulu and West Sumatra Provinces.

Data collection

The data utilized in this investigation comprised a satellite image obtained from the Landsat 8 Enhanced Thematic Mapper (ETM) instrument, with an ensured cloud coverage of less than 10%. Landsat 8, launched in 2013, represents the latest advancement in the series of LANDSAT satellite projects. The instrument is outfitted with two sensors: the operational land imager (OLI) and the thermal infrared sensor (TIRS). The OLI sensor is equipped with nine bands. Each band possesses a spatial resolution of 30 meters. The channels under consideration encompass coastal or aerosol, blue, green, red, near-infrared (NIR), short-wave infrared one (SWIR1), short-wave infrared two (SWIR-2), and Cirrus. The only exception is the panchromatic band, which has a high spatial resolution of 15 meters. The comparison of the two sensors shows that Thermal Infrared (TIR) possesses two bands: Thermal Infrared one (TIR1) and Thermal Infrared two (TIR2). Both bands exhibit a spatial resolution of 100 meters (Shidiq and Ismail, 2016). Landsat 8 orbits the Earth at an average altitude of 705 kilometers (km), with an inclination angle of 98.2°. Citra Landsat 8 also supports monitoring research because it is free and has time series data. Table 1 shows the acquisition of imagery data utilized.

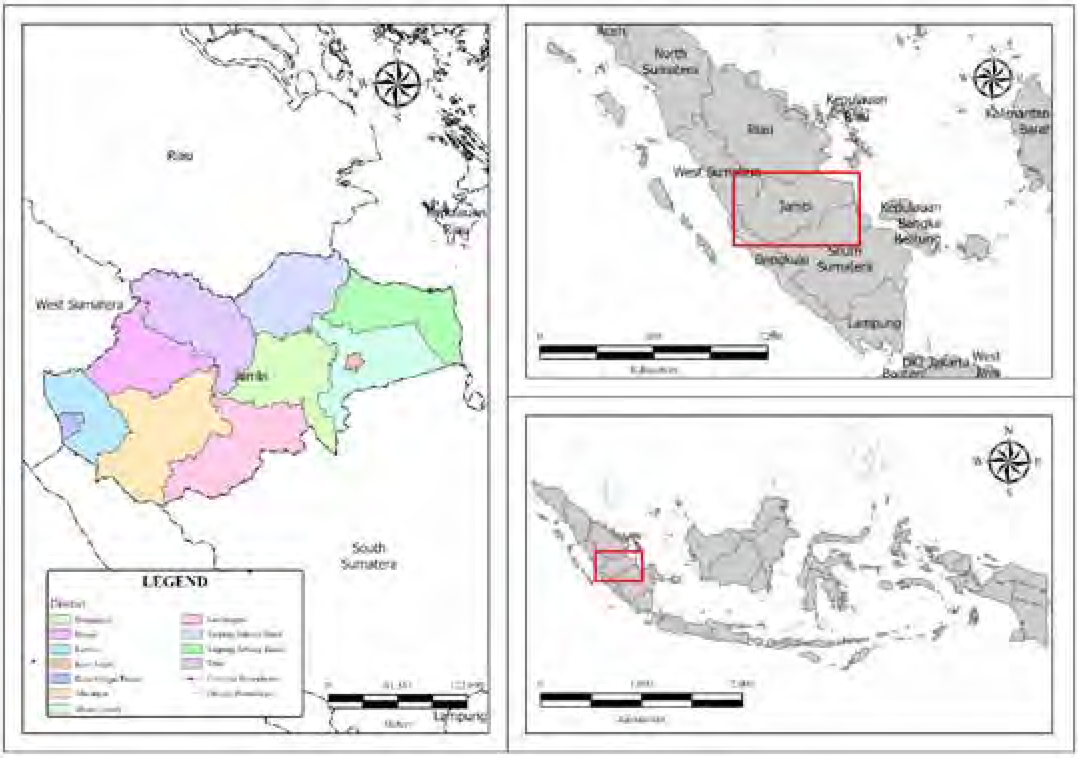


Fig. 1: Geographic location of the study area in Jambi, Indonesia

Table 1: Imagery data utilized in the current study

Path dan row	Acquisition 2014	Acquisition 2019–2020
Path 125, Row 062	2014/07/16	02/05/2019
Path 126, Row 062	2014/06/21	02/05/2019
Path 126, Row 061	2014/06/21	02/05/2019
Path 125, Row 061	2014/09/02	15/08/2019
Path 124, Row 061	2014/07/25	20/04/2020

Land cover mapping

Land cover mapping has three phases. The first stage is preprocessing imagery data. This stage involves merging multispectral (layer stacking) canals, image cropping, radiometric correction, and radiometric calibration. This stage is accomplished to overcome the inaccuracy of remote sensing and error in measuring devices (Ramana and Rajesh, 2018). At this stage, the digital number (DN) value is changed to reflect the value shape and facilitate Eq. 1 to obtain the Reflektan value (USGS, 2019).

$$\rho\lambda' = M\rho \; x \; Qcal + A\rho, \qquad (1)$$

Where;

Mρ : The band-specific multiplicative rescaling factor

Aρ : Band-specifik additive rescaling factor

ρλ′ : The uncorrected top-of-atmosphere (TOA) reflectance angle of the sun

Qcal : Pixel value (DN)

The following stages are the makers of the region of interest (ROI) and spectral signature. ROI serves as a sampling area in classification and guidance in assessing classification accuracy level. Furthermore, ROI serves as a sample in extracting spectral signature values, which are further utilized in maximum likelihood method preparation. ROI is derived from Google Earth data, which present Earth images with high accuracy of spatial and temporal resolutions. The subsequent phase involves land cover classification. The classification approach employed in this study is the maximum likelihood classification method. It was implemented using ENVI 5.1 software. This method was also utilized by Hossain *et al*. (2016), who classified land cover with agricultural land, built-up land classes, plantations, open land, and forests. Furthermore, this approach was employed by Butt et al. (2015) to separate agricultural land, settlements, empty land, vegetation, and water bodies. This method also separates oil palm land from other land covers. Maximum likelihood classification is derived from the assumption that the pixel value distribution sampled from each class obeys the Bayesian Decision Rule, where each class probability is the same for normally distributed pixel values. This method's advantage is that data processing does not take long. After obtaining classification results, the researchers utilized GIS software to calculate the area of each land cover, particularly oil palm land area, in 2014 and 2019. The aeronautical reconnaissance coverage geographic information system (ArcGIS) 10.1 software was employed in the present study to transform the categorization outcomes into vector data.

Accuracy assessment

The accuracy assessment for this study used a confusion matrix by considering the overall accuracy and Kappa Coefficient. This accuracy assessment was utilized for similar research (de Almeida *et al*., 2020). Confusion matrix is an effective method for explaining the overall accuracy of each classification category and fault classification. In this study, a sample point for accuracy assessment was obtained from Google Earth imagery and field observation interpretation. Within the field observation, the validation class was the oil palm class, and documentation and plotting utilizing the global positioning system (GPS) were conducted. Thirty sample points in the oil palm were collected to validate the oil palm area. However, other classes were validated using the ROI collected through Google Earth.

Land cover change analysis

The GIS overlay method can identify the threaded land between two temporal resolutions. The overlay analysis was performed using the spatial analysis toolbox in ArcGIS 10.1 software. Various data processing methods, including intersection, union, erase, identity, spatial join, symmetrical difference, and update, are available within this toolbox. In this study, the union method was employed. This technique facilitates the overlay of two or more sets of vector or polygon data at the same location, allowing for a comprehensive overview of different features within a single area. Consequently, the results provide detailed insights into the changes in land cover within the same locations by overlaying the land cover data of Jambi Province for 2014 and 2019. As stated by Butt *et al*. (2015), this method can describe land types that change in the research area. These land types are displayed with the two-way cross-matrix. This method can also calculate the changing land area of the two data in two temporal resolutions.

RESULTS AND DISCUSSION

Classification results indicate that the land images obtained by Landsat 8 imagery are bare land, water bodies, built-up areas, and forests. Oil palm plantations, other vegetation, and other land covers are also included. Determining a land cover type is based on the visual interpretation of the medium resolution of Landsat 8 imagery combined with high-resolution imagery from Google Earth. This study emphasizes the land cover of oil palm plantations and uses of other land cover types to analyze land conversion in the study area. The interpretation results of the land cover in Jambi Province are shown in Table 2.

The application of the maximum likelihood method in classification demonstrates a high level of accuracy, as indicated by an overall accuracy rate of 96.61% and a kappa coefficient of 0.94 for land cover in 2014. The results of the land cover categorization conducted in 2019 demonstrate an overall accuracy rate of 89% and a kappa coefficient of 0.7. The aforementioned accuracy metric demonstrates the potential utility of land cover classification outcomes for subsequent research. The disparity in precision rates between 2014 and 2019 can be attributed to variations in the duration of data acquisition for individual Landsat 8 image scenes and various atmospheric interferences, including cloud cover and smoke emanating from forest fires. The comparison of the confusion matrices for 2014 and 2019 is shown in Tables 3 and 4, respectively.

Table 2: Landsat 8 and Google Earth images interpretation derived from each land cover class

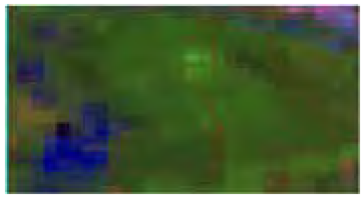
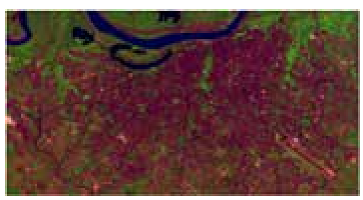
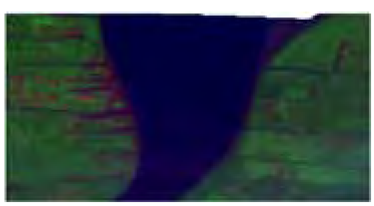
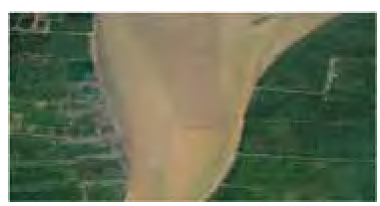
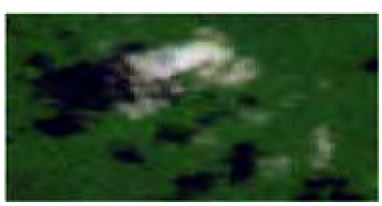
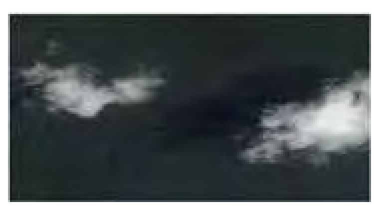
Classification	Landsat 8 imagery (false color composite 6,5,3)	Googel Earth imagery
Privately owned oil palm plantations		
Oil palm plantation land owned by small farmers		
Other vegetation		
Bareland		
Built-up area		
Water body		
Other (cloud and shadow)		

Table 3: Confusion matrix for land cover classification in 2014

Class	Oil palm	Other vegetation	Built-up	Bare land	Water body	Cloud	Shadow	Total
Oil palm	331165	42636	447	2521	11	1015	31	377826
Other vegetation	32553	1733371	48	206	9	0	6	1766193
Built-up	4606	2490	15210	3694	32	426	10	26468
Bare land	982	1735	904	113275	15	138	3	117052
Water	0	79	0	2	72350	0	0	72431
Cloud	3664	1286	104	2691	1017	719857	0	728619
Shadow	110	1436	0	3	2	0	2657	4208
Total	373080	1783033	16713	122392	73436	721436	2707	3092797

Table 4: Confusion matrix for land cover classification in 2019

Class	Oil palm	Other vegetation	Built-up	Bare land	Water body	Cloud	Shadow	Total
Oil palm	236597	225001	52	105	16	24	235	462030
Other vegetation	15560	2145158	0	40	1	546	80	15002
Built-up	3542	1299	9225	206	104	546	80	15002
Bare land	1326	15572	242	25696	665	740	253	44494
Water	0	18	0	0	67791	0	5	67814
Cloud	1064	2793	83	238	3	104498	66	108745
Shadow	184	49076	0	34	0	39	16385	65718
Total	258273	2438917	9602	26319	68580	105854	18063	2925608

Table 5. Land cover area of Jambi Province in 2014 and 2019

Land cover classes	Width of the area (ha)	
	2014	2019
Oil palm	2071345	2110545
Other vegetation	1692777	1071001
Water body	30427	33736
Bare land	336059	660121
Built-up area	43845	209203
Shadow	30390	217766
Cloud	426723	629181
Total	4631566	4931554

GIS technology is utilized to calculate area. The findings of the categorization analysis show that the predominant land cover in the Jambi Province region mostly comprises oil palm plantations. These plantations encompass privately held land dedicated to oil palm cultivation and smallholder plantations. In 2014, the proportion of land dedicated to oil palm cultivation in Jambi Province accounted for approximately 45% of the overall land area. This amount is equal to a total land area of 2,071,344.5 ha. In 2019, the area of oil palm land reached approximately 43% of the total area of Jambi Province. However, bare land increased by 324,063 ha in 5 years. The built-up land area increased by 165,358 ha. The bare land/ land area increases because of land clearing and deforestation, making way for private oil palm plantations and community gardens. Other vegetation in this study includes forest and grass areas. The area of this vegetation decreased. The land area for each classification result is shown in Table 5.

This study used the most popular conventional classification method, namely, the maximum likelihood classifier, for mapping and analyzing the spatial patterns of land cover change in Jambi Province. This method still has limitations due to the amount of training sample, and these limitations affect the classification accuracy (Rosyidy *et al*., 2023). The maximum likelihood classifier cannot handle complex images, resulting in the incorrect classification of many pixels (Deilmai *et al*., 2014). Some studies introduced novel machine learning approaches for land cover mapping, demonstrating increased classification accuracy and significantly reduced time consumption. Nasiri *et al*. (2022) employed a machine learning approach, particularly the random forest classifier, for mapping and classifying land cover using Landsat 8 and Sentinel 2 imagery. Other researchers also utilized machine learning approaches with cloud computing tools (Google Earth Engine), such as support vector machine (SVM), classification and regression trees (CART), and artificial neural network (ANN) (Samimi and Mohadesi, 2023); thus, a significant rule is provided for developing and improving land cover mapping and change analysis, particularly in detecting spatial patterns of oil palm plantations (Li *et al*., 2020). However, the integration of advancements in information technology in the remote sensing and GIS applications for land cover mapping must be incorporated to result in comprehensive and accurate research outcomes.

Spatial and temporal patterns of oil palm plantation

Jambi Province has a plain topography in the east and tends to have a mountainous and hilly landscape in the west. Oil palm plantations are frequently located in topographically plain or gently sloping regions. Oil palm plantations in hilly regions characterized by high altitudes and steep slopes are generally less prevalent than those in comparatively level locations in terms of geographic distribution and time. The results of this study align with those of previous research in Malaysia, indicating that oil palm plantations are found in areas previously forested with lowland topography (Williamson *et al*., 2020). Research in Myanmar also indicated something similar; in particular, oil palm plantations are concentrated in coastal or lowland areas with plain topography (Poortinga *et al*., 2019). In 2014, Tebo District had the largest expanse of oil palm plantations, with a total area of 369,403.4 ha. Conversely, Jambi City had the smallest area of oil palm plantations, amounting to only 2,612.5 ha. In 2019, the Serolangun Regency exhibited the highest extent of oil palm plantations, encompassing a total land area of 1,434,556.3 ha. Conversely, the Sungai Banyak City possessed the largest oil palm plantation area, spanning a total of 1,037.6 ha. An observable increase in the total land area dedicated to oil palm crops was found between 2014 and 2019. The expansion of oil palm plantations was observed in the Districts of Bungo, Merangin, West Tanjung Jabung, and Kerinci. By contrast, other districts experienced a decrease in the total area of land designated for oil palm plantations. The observed phenomena can be attributed to the deforestation of oil palm trees, which is undertaken to allow the development of new oil palm seedlings. Consequently, a significant portion of the area transformed into uninhabited terrain. Sarolangun District experienced the most significant increase in oil palm land area, with a substantial surge of 1,265,155 ha. The second district is West Tanjung Jabung, encompassing an area of 91,237.15 ha. The graph depicting the fluctuations in oil palm cultivation across various districts is presented in Fig. 2. Increasing the area of oil palm plantations is intended to increase palm oil productivity even though it hurts environmental aspects, such as encouraging carbon emissions and biodiversity loss. However, increasing palm oil productivity can be accomplished through environmentally friendly methods. Previous research indicated that increasing palm oil productivity can be realized by replanting oil palms without opening new lands. Replanting oil palm at 4% every year, accompanied by enhanced management practices or improved cultivars, can optimize the increase in palm oil production (Zhao *et al*., 2023).

Land utilization and land cover change

The analysis showed the land utilization and land cover changes in the Jambi area over the last 5 years. Table 6 shows that significant changes in land utilization and land cover were found between 2014 and 2019. Remote sensing with Google Earth and Landsat can contribute to mapping land utilization and land cover in the Jambi area. This condition proves that remote sensing contributes to the success of mapping complex land cover (Mahdianpari *et al*., 2018). Parameters for land change are shown in Table 6. Pixel parameters were used to calculate land areas.

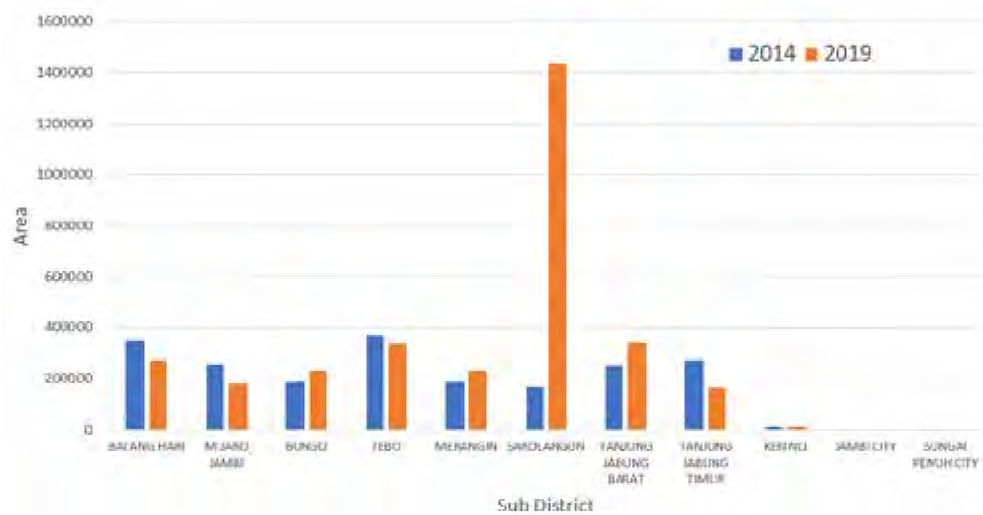


Fig. 2: Changes in the oil palm plantation areas across various districts during 2014–2019

Table 6: ROI collection within this study

ROI	ROI (Broad category)	2014		2019		Source
		Pixel	Area (ha)	Pixel	Area (ha)	
Oil palm	Forest	373,080	33,577.20	25,273	23,244.57	Google Earth
Other vegetation		1,783,033	160,472.97	2,438,917	219,502.53	Google Earth
Water body	Water Body	73,436	6,609.24	6,858	6,172.20	Google Earth
Bare land	Bare land	122,392	11,015.28	26,319	2,368.71	Google Earth
Built-up area	Built-up area	16,713	1,504.17	9,602	864.18	Google Earth
Shadow	Other land cover	2,707	243.63	1,063	1,625.67	Landsat 8
Cloud		721,436	64,929.24	105,854	9,526.86	Landsat 8

The parameters in sensing mapping can be derived from objects, pixels, or subpixels (fractional images) (Li *et al*., 2019). Table 6 shows that some areas are covered by shadow and cloud. This result is the same as that stated by former literature explaining that Indonesia, a tropical region, has a significant obstacle in the form of persistent cloud cover; thus, remote sensing opportunities are limited (Van der Laan *et al*., 2018).

Table 6 shows the increase in oil palm land area. The use and change of land in Jambi Province to oil palm land can be caused by increasing productivity to meet the need for oil palm through expansion driven by local factors, economic profitability, market preferences, and foreign factors (Varkkey *et al*., 2018). Moreover, the changes in land use and cover in Table 6 can be caused by economic and political incentives for oil palm cultivation, which ultimately encourages land conversion or changes in land use (Cisneros *et al*., 2021). If corporations remain dedicated to fulfilling existing demands and enhancing productivity, the oil palm industry is projected to gain a 20% growth in plantation areas from 2014 to 2040. This growth can be attributed to the swift expansion of oil palm plantations (Afriyanti *et al*., 2016). Generated land used as a building area can be affected by changing forest land or other vegetation into oil palm plantations. This condition can be caused by the distance from roads, distance from oil palm plantations, slope, distance from rivers and settlements, and altitude (Nurwanda *et al*., 2016). In Jambi Province, changes in land use and cover can also be caused by the development of the transmigration program in the Jambi region (Yanita *et al*., 2019). The preparation of oil palm plantation areas or oil palm rejuvenation areas can increase bare land. This area can be the remains of a forest burning area prepared for developing other land or an oil palm plantation area (Prasetyo *et al*., 2016).

Smallholders and deforestation

Jambi is one of the provinces on Sumatra Island experiencing rapid deforestation (Rustiadi *et al*., 2018). Fig. 2 shows that the land structures in Jambi are generally other vegetation areas (plantations or agriculture) and forests. The existing development area is still limited even though it is spread across every district in Jambi. Deforestation in Jambi generally intends to change the land from forest to other vegetation areas or from one vegetation to another vegetation. Plantation and agricultural areas in Jambi are dominated by rubber and oil palm plantations. Changes in land cover due to land clearing and oil palm plantations occur, with an increase in oil palm plantations reaching approximately 120 thousand ha in 2014. This scenario decreased the forest land amount in Jambi Province (Nurwanda *et al*., 2016). The robust growth of the export industry, which is supported by legal ambiguity and strong internal security measures for acquired land (Krishna *et al*., 2017), drives land change and further deforestation in Jambi. These land changes increase CO_2 emissions in the atmosphere. The extent of CO_2 emissions arising from land-use change scenarios is impacted by modifications in the policy scenarios that control them. Enhanced policy enforcement can have a significant mitigation effect in terms of land utilization change, as it can reduce deforestation by 50%–53%. The total area of private and community oil palm plantations in 2020 was 827,969.54 ha, with the total area of community plantations being twice the private plantations area (Fig. 3). Land changes in Jambi Province are dominated by smallholder plantations because of changes in Jambi land; these plantations are affected by transmigration program, which is integrated into oil palm plantations development through partnership programs (Yanita *et al*., 2019). Additionally, land acquisition in Jambi is generally accomplished through forest land utilization and market transactions. Partnership-based transmigration programs have been developing in Indonesia since 1980. This partnership program allows small farmers to receive financial and technical assistance for oil palm plantation management and distribution of the harvest obtained (Krishna *et al*., 2017). This program was carried out to encourage the development of people's plantations to grow. The area of oil palm land owned by farmers increased by approximately 1,000 ha from 2015 to 2018, and a significant increase of approximately 38,899 ha occurred in 2016–2017. Overall, the land area for oil palm (private and community oil palm plantations) can still increase if oil palm productivity in Indonesia is increased to emphasize that the extensification process and market influence factors are vital (Van der Laan *et al*., 2018). This opportunity arises because of the motivation to fulfill domestic and international demands. Indonesia is expected to produce 51 million tons of CPO by 2025, with an additional requirement of 6 million ha of land productivity remaining as it is today (Khatiwada *et al*., 2018).

A significant increase in the land owned by smallholders in 2016–2017 could indicate large-scale land clearing in the former year. In 2015, Indonesia experienced the worst fires since 1998. The fires led to the dispersion of smoke haze to neighboring countries of Indonesia. For land preparation purposes, this situation was also utilized by many organizations, including oil palm plantations and forestry firms. During the 2001–2015 period in Jambi, 20.67% of the fire incident area was converted into forest plantations, and 27.06% was converted into oil palm plantations. Moreover, 52.27% of the remaining land in Jambi was owned by small planters/communities; the initial vegetation of the land change was scrub and disturbed secondary forest (Prasetyo *et al*., 2016). Hence, in the year before 2016, smallholders dominated land clearing to fulfill the economic and social activities. Furthermore, the high quantity of land conversion to oil palm land caused by smallholders shows that smallholders play an essential role in preventing further deforestation not only in Jambi but also throughout Indonesia. The agricultural land expansion process is affected by the activities of large-scale companies, local elites, and smallholders (Barbier, 2020). The data from BPS RI Provinsi Jambi (2023b) show that Jambi Province had 187,756 oil palm farmers in 2013. The number of oil palm farmers increases yearly. In 2018, Jambi Province had 221,711 palm oil farmers. In particular, the number of oil palm farmers increased by 33,955 in 5 years. Farmers tend to expand oil palm plantations in the forest. In Indonesia, 68% of smallholder oil palm plantations are illegally located in forest areas (Nurfatriani *et al*., 2019). The Indonesian government has ratified Keputusan Presiden Republik

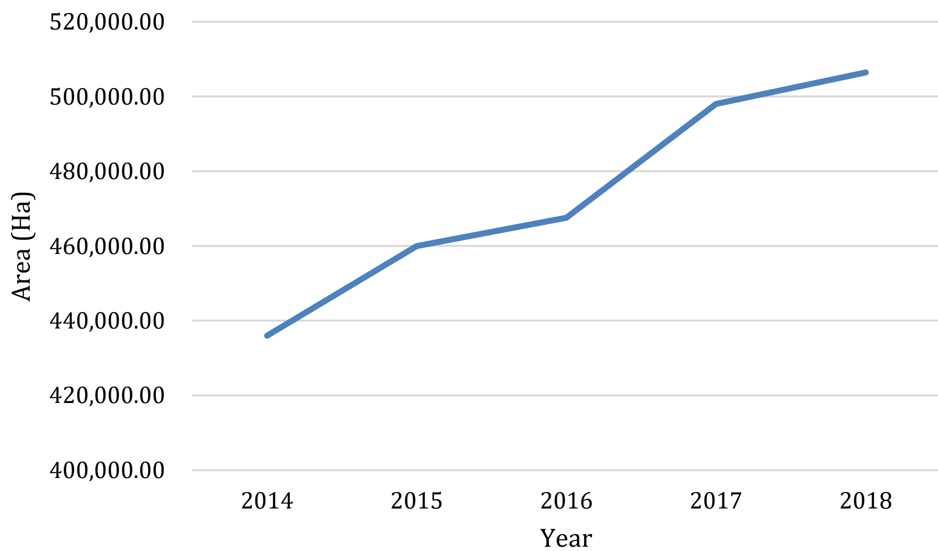


Fig. 3: Graph of the increase in smallholder oil palm land area in 2014–2018 (BPS RI Provinsi Jambi, 2023a)

Indonesia Nomor 9 Tahun 2023 tentang Satgas Penyempurnaan Tata Kelola Industri Kelapa Sawit dan Optimalisasi Pendapatan Negara (the Presidential Decree of the Republic of Indonesia Number 9 of 2023 Concerning the Task Force for Improving Palm Oil Industry Governance and Optimizing State Revenue) (Pemerintah Indonesia, 2023a). This regulation was passed by considering the development of the palm oil commodity-based industry, which continues to increase. However, obstacles in the governance of the palm oil industry remain. These obstacles can finally result in loss of state revenue from taxes and/or nontaxes. This decision by the president of the Republic of Indonesia is a tool to suppress the growth of the illegal and poorly managed palm oil industry. Indonesia has also explained the licensing of business activities in forest areas, including palm oil businesses, in Undang-Undang RI No. 6 Tahun 2023 tentang Penetapan Peraturan Pemerintah Pengganti Undang-Undang No. 2 Tahun 2022 tentang Cipta Kerja menjadi Undang-Undang (Law of the Republic of Indonesia No. 6 of 2023 Concerning Stipulation of Government Regulations in Lieu of Law No. 2 of 2022 Concerning Job Creation becomes law) in articles 110 A and 110 B. Article 110 A states that every person who carries out business activities that have been established and has a location permit and/or business permit in the plantation sector by an authorized official before its enactment Law Number 11 of 2020 Concerning Job Creation but have not fulfilled the requirements in accordance with the provisions of laws and regulations in the forestry sector must complete the requirements no later than November 2, 2023. If the requirements are not completed within the specified time, these individuals would be subjected to administrative fines, and/or the sanction of the requested permit would be revoked. Article 110 B states that every person who carries out business activities in forest areas without a business permit before November 2, 2020, would be subjected to temporary business permit sanctions, payment of administrative fines, and/or government coercion (Pemerintah Indonesia, 2023b). Oil palm plantations provide a positive economic effect. Otherwise, the process increases the deforestation rate, resulting in ecosystem services loss. Sharma *et al.* (2019) found that when oil palm expansion is conducted utilizing a sustainable intensification scenario, a significant compromise is found between the supply of ecosystem services and oil palm yields. Therefore, a significant opportunity to reduce the deforestation rate from the smallholder land clearing process can be found by increasing smallholders' productivity. Nevertheless, the challenge is increasing smallholders' productivity by shifting the extensification process to the intensification process; the reason is that smallholders' productivity only reaches half of the company's productivity because smallholders' productivity is approximately half of that of the company (Purnomo *et al*., 2019). Furthermore, smallholders must still be involved in preventing further deforestation. Smallholder involvement in preventing further deforestation and forest degradation makes deforestation prevention projects inclusive, realistic, and long-lasting while ensuring smallholder livelihoods in the long term (Duker *et al*., 2019). Thus, oil palm cultivation can potentially support people's income, particularly small farmers. However, the increasing growth in land clearing every year shows that palm oil productivity still depends on extensification efforts. These limitations can be triggered by farmers' lack of knowledge about other efforts that can be utilized to increase palm oil productivity, such as sustainable intensification scenarios. The intensification scenario includes rejuvenating oil palm plants by replacing old plants with oil palm seeds, chopping oil palm branches and stems, planting cover crops, and soil conservation. This intensification scenario is a middle way between meeting the economic needs of the community, which supports regional economic development, and fulfilling the responsibility of preventing damage to the environment.

CONCLUSION

The present study effectively employed Landsat 8 satellite imagery to delineate spatially the extent of oil palm plantations, encompassing a land area of 2,071,345 ha in 2014 and 2,110,545 ha in 2019. A notable expansion of oil palm plantations in Jambi Province was determined between 2014 and 2019. This expansion resulted in an increase of approximately 39.2 thousand ha. This expansion can be attributed to the practices of land clearing and deforestation. Over the past 5 years, increases in bare land and built-up land in Jambi Province have been observed. This scenario results in a decrease in the amount of vegetated land. Between 2014 and 2019, a notable expansion of 324,063 ha was found in unoccupied land, accompanied by a concurrent growth of 165,358 ha in developed land. The findings of this study indicate that the presence of oil palm plantations and the topographical characteristics of the land have a positive correlation. In particular, locations with relatively plain terrain exhibit a high concentration of oil palm plantations, whereas regions with high altitudes and steep slopes tend to have a low prevalence of such plants. The oil palm land area of small-scale farmers notably increased by 1,000 ha throughout the period spanning from 2014 to 2018. The largest observed expansion of approximately 38,889 ha occurred during the 2016–2017 period. The augmentation of oil palm production yields economic advantages for society but is accompanied by potential environmental ramifications. Hence, devising interventions congruent with the economic advantages for society and promoting sustainable and ecologically sound oil palm cultivation are imperative. Moreover, the government must develop and implement many effective policies to achieve substantial mitigation outcomes in relation to alterations in land utilization. Hence, the government's involvement as a regulating body is essential in mitigating the deforestation rate while simultaneously ensuring that the local economy, particularly in relation to oil palm productivity, remains unaffected. In addition, the community responsible for oil palm management can significantly contribute toward mitigating deforestation rates by adopting sustainable intensification strategies in their practices.

AUTHOR CONTRIBUTIONS

M.K. Rosyidy participated in writing the original draft, reviewing and editing, preparing pictures and tables of study results, and drawing conclusions. E. Frimawaty was the corresponding author, supervising the study, obtaining funding, and conceptualization, participated in data analysis and interpretation.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

°	Degrees
′	Minutes
°C	Degrees Celsius
–	Until
%	Percent
ANN	Artificial Neural Network
ArcGIS	Aeronautical reconnaissance coverage geographic information system
BMKG	Badan Meteorologi, Klimatologi, dan Geofisika (Meteorological, Climatological and Geophysical Agencies)
BPS RI	Badan Pusat Statistik Republik Indonesia (Central Statistics Agency of the Republic of Indonesia)
CART	Classification and regression trees
CO_2	Carbon dioxide
CPO	Crude palm oil
DN	Digital number
E	East
ETM	Enhanced thematic mapper
GIS	Geographic information system
GPS	Global positioning system
Ha	Hectares
Km	Kilometers
km^2	Square kilometers
Mha	Million hectares
NIR	Near-infrared
NSMD	Nonstate market-driven
OLI	Operational Land Imager
ROI	Region of Interest
S	South
SVM	Support Vector Machine
TOA	Top-of-atmosphere
SWIR-1	short-wave infrared one
SWIR-2	Short-wave infrared two
TIR	Thermal Infrared
TIR1	Thermal Infrared one
TIR2	Thermal Infrared two
TIRS	Thermal infrared sensor

REFERENCES

Adimalla, N.; Taloor, A.K., (2020). Hydrogeochemical investigation of groundwater quality in the hard rock terrain of South India using Geographic Information System (GIS) and groundwater quality index (GWQI) techniques. Groundwater Sustainable Dev., 10: 100288 **(16 pages)**.

Afriyanti, D.; Kroeze, C.; Saad, A., (2016). Indonesia palm oil production without deforestation and peat conversion by 2050. Sci. Total Environ., 557–558: 562–570 **(9 pages)**.

Alesina, A.; Gennaioli, C.; Lovo, S., (2019). Public Goods and Ethnic Diversity: Evidence from Deforestation in Indonesia. Economica, 86: 32–66 **(35 pages)**.

Asen, J.J.; Terna, K.G.; Tertsea, I.E., (2018). Assessing the status of yandev forest reserve using remote sensing and geographic information system (GIS) techniques. Asian J. Res. Agric. For., 2(2): 1–13 **(13 pages).**

Austin, K.G.; Schwantes, A.; Gu, Y.; Kasibhatla, P.S., (2019). What causes deforestation in Indonesia? Environ. Res. Lett., 14: 024007 **(10 pages).**

Barbier, E.B., (2020). Long run agricultural land expansion, booms and busts. Land Use Policy, 93: 103380 (**11 pages)**.

BPSRI Provinsi Jambi, (2023a). Luas tanaman perkebunan menurut jenis tanaman dan kabupaten/kota (Hektar), 2014-2018.

BPSRI Provinsi Jambi, (2023b). Jumlah Petani Tanaman Perkebunan menurut Jenis Tanaman (Rumah Tangga), 2013-2018.

Butt, A.; Shabbir, R.; Ahmad, S.S.; Aziz, N., (2015). Land use change mapping and analysis using Remote Sensing and GIS: A case study of Simly watershed, Islamabad, Pakistan. Egypt. J. Remote Sens. Space. Sci., 18: 251–259 **(9 pages).**

Carlson, K.M.; Heilmayr, R.; Gibbs, H.K.; Kremen, C., (2018). Effect of oil palm sustainability certification on deforestation and fire in Indonesia. Proc. Natl. Acad. Sci. U.S.A., 115: 121–126 **(6 pages).**

Cisneros, E.; Kis-Katos, K.; Nuryartono, N., (2021). Palm oil and the politics of deforestation in Indonesia Standard. J. Environ. Econ. Manage., 108: 102453 **(19 pages).**

Costa, H.; Foody, G.M.; Boyd, D.S., (2018). Supervised methods of image segmentation accuracy assessment in land cover mapping. Remote Sens. Environ., 205: 338–351 **(4 pages)**.

de Almeida, A.S.; Vieira, I.C.G.; Ferraz, S.F.B., (2020). Long-term assessment of oil palm expansion and landscape change in the eastern Brazilian Amazon. Land Use Policy, 90: 1–8 **(8 pages)**.

Deilmai, B.R.; Ahmad, B.B.; Zabihi, H., (2014). Comparison of two Classification methods (MLC and SVM) to extract land use and land cover in Johor Malaysia. IOP Conf. Ser.: Earth Environ. Sci., 20(1): 012052 **(7 pages)**.

Duker, A.E.C.; Tadesse, T.M.; Soentoro, T.; de Fraiture, C.; Kemerink-Seyoum, J.S., (2019). The implications of ignoring smallholder agriculture in climate-financed forestry projects: empirical evidence from two REDD+ pilot projects. Clim. Policy, 19: S36–S46 **(11 pages)**.

Hashemi, S.A., (2018). Ecological capability evaluation for afforestation and forest expansion usingeographic information system (GIS) in management area of Caspian Sea. An. Acad. Bras. Ciênc., 90(04): 3761–3768 **(9 pages)**.

Heilmayr, R.; Carlson, K.M.; Beneditct, J.J., (2020). Deforestation spill overs from oil palm sustainability certification. Environ. Res. Lett., 15: 075002 **(16 pages)**.

Hossain, M.S.; Bujang, J.S.; Zakaria, M.H.; Hasyim, M.H., (2016). Marine and human habitat mapping for the coral triangle initiative region of Sabah using Landsat and Google Earth imagery. Mar. Policy, 72: 176–191 **(16 pages).**

Kementerian Pertanian RI., (2020). Statistik Perkebunan Indonesia Komoditas Kelapa Sawit Tahun 2018–2020. Sekretariat Direktorat Jenderal Perkebunan, Kementerian Pertanian, Jakarta.

Khatiwad, D.; Palmén, C.; Silveira, S., (2018). Evaluating the palm oil demand in Indonesia: production trends, yields, and emerging issues. Biofuels, 12(2): 135–147 **(13 pages)**.

Krishna, V.V.; Kubitza, C.; Pascual, U.; Qaim, M., (2017). Land markets, Property rights, and Deforestation: Insights from Indonesia. World Dev., 99: 335–349 **(15 pages)**.

Li, G.; Lu, D.; Moran, E.; Calvi, M.F.; Dutra, L.F.; Batistella, M., (2019). Examining deforestation and agropasture dynamics along the Brazilian TransAmazon Highway using multitemporal Landsat imagery. GIScі. Remote Sens., 56: 161–183 **(23 pages)**.

Li, W.; Fu, D.; Su, F.; Xiao, Y., (2020). Spatial–Temporal Evolution and Analysis of the Driving Force of Oil Palm Patterns in Malaysia from 2000 to 2018. ISPRS Int. J. Geo. Inf., 9(4): 280 **(22 pages)**.

Ling, F.; Foody, G.M.; Li, X.; Zhang, Y.; Du, Y., (2016). Assessing a temporal change strategy for sub-pixel land cover change mapping from multi-scale remote sensing imagery. Remote Sens., 8(8): 642 **(23 pages)**.

Mahdianpari, M.; Salehi, B.; Rezaee, M.; Mohammadimanesh, F.; Zhang, Y., (2018). Very deep convolutional neural networks for complex land cover mapping using multispectral remote sensing imagery. Remote Sens., 10(7): 1119 **(21 pages)**.

Matin, M.A.; Chitale, V.S.; Murthy, M.S.R.; Uddin, K.; Bajracharya, B., (2017). Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information system and historical fire data. Int. J. Wildland Fire., 26: 276–286 **(11 pages)**.

Nasiri, V.; Deljouei, A.; Moradi, F.; Sadeghi, S.M.M.; Borz, S.A., (2022). Land Use and Land Cover Mapping Using Sentinel-2, Landsat-8 Satellite Images, and Google Earth Engine: A Comparison of Two Composition Methods. Remote Sens., 14(9): 1977 **(18 pages).**

Nurfatriani, F.; Ramawati; Sari, G.K.; Komarudin, H., (2019). Optimization of crude palm oil fund to support smallholder oil palm replanting in reducing deforestation in Indonesia. Sustainability, 11: 4914 **(16 pages)**.

Nurwanda, A.; Zain, A.F.M.; Rustiadi E., (2016). Analysis of land cover changes and landscape fragmentation in Batanghari Regency, Jambi Province. Procedia–Social Behav. Sci., 227: 87–94 **(8 pages)**.

Payus, C.M.; Sentian, J., (2022). Satellite imagery system in malaria transmission resulting from the land use/land cover change. Global J. Environ. Sci. Manage., 8(4): 545–560 **(16 pages)**.

Pemerintah Indonesia, (2023a). Keputusan Presiden Republik Indonesia Nomor 9 Tahun 2023 tentang Satgas Penyempurnaan Tata Kelola Industri Kelapa Sawit dan

Optimalisasi Pendapatan Negara. Sekretariat Negara, Jakarta **(8 pages)**.

Pemerintah Indonesia, (2023b). Undang-Undang RI No. 6 Tahun 2023 tentang Penetapan Peraturan Pemerintah Pengganti Undang-Undang No. 2 Tahun 2022 tentang Cipta Kerja menjadi Undang-Undang. Sektretariat Negara, Jakarta **(1127 pages).**

Poortinga, A.; Tenneson, K.; Shapiro, A.; Nquyen, Q.; Aung, K.S.; Chistie, F.; Saah, D., (2019). Mapping Plantations in Myanmar by Fusing Landsat-8, Sentinel-2 and Sentinel-1 Data along with Systematic Error Quantification. Remote Sens., 11(7): 831 **(19 pages)**.

Prasetyo, L.B.; Dharmawan, A.H.; Nasdian, F.T.; Ramdhoni, S., (2016). Historical forest fire occurrence analysis in Jambi Province during the period of 2000–2015: Its distribution and land cover Trajectories. Procedia Environ. Sci., 33: 450–459 **(10 pages).**

Purnomo, E.P.; Ramdani, R.; Agustiyara; Tomaro, Q.P.V.; Samidjo, G.S., (2019). Land ownership transformation before and after forest fires in Indonesian palm oil plantation areas. J. Land Use Sci., 14(1): 37–51 **(15 pages)**.

Purnomo, H.; Okarda, B.; Dermawan, A.; Ilham, Q.P.; Pacheco, P.; Nurfatriani, F.; Suhendang, E., (2020). Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. For. Policy Econ., 111: 102089 **(12 pages).**

Ramana, R.K.V.; Rajesh, K.P., (2018). Land cover classification using landsat-8 optical data and supervised classifiers. Int. J. Eng. Technol., 7: 101–104 **(4 pages)**.

Rosyidy, M.K.; Wibowo, A.; Sidiq, I.P.A., (2023). Oil palm mapping based on machine learning and non-machine learning approach using Sentinel-2 imagery. AIP Conference Proceeding. 2482(1): 070001 **(12 pages)**.

Rustiadi, E.; Barus, B.; Iman, L.S.; Mulya, S.P.; Pravitasari, A.E.; Antony, D., (2018). Land use and spatial policy conflicts in a rich-biodiversity rain forest region: The case of Jambi Province, Indonesia. Exploring sustainable land use in monsoon Asia, 277–296 **(20 pages)**.

Sabajo, C.R.; le Maire, G.; June,T.; Meijide, A.; Roupsard, O.; Knohl, A., (2017). Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. Biogeosciences, 14: 4619–4635 **(17 pages)**.

Samimi, M.; Mohadesi, M., (2023). Size estimation of biopolymeric beads produced by electrospray method using artificial neural network. Particulate Science and Technology, 41(3): 371-377 **(7 pages).**

Schebek, L.; Mizgajski, J.T.; Schaldach R.; Wimmer, F., (2018). Land-Use Change and CO_2 Emissions Associated with Oil Palm Expansion in Indonesia by 2020. From Science to Society, 49–59 **(11 pages)**.

Sharma, S.K.; Baral, H.; Laumonier, Y.; Okarda, B.; Komarudin, H.; Purnomo, H.; Pacheco, P., (2019). Ecosystem services under future oil palm expansion scenarios in West Kalimantan, Indonesia. Ecosyst. Serv., 39: 100978 **(11 pages)**.

Shidiq, I.P.A.; Ismail, M.H., (2016). Stand age model for mapping spatial distribution of rubber tree using remotely sensed data in Kedah, Malaysia. Jurnal Teknologi, 78: 239–244 **(6 pages)**.

Suharyanto, A.; Maulana, A.; Suprayogo, D.; Devia, Y.P.; Kurniawan, S., (2023). Land surface temperature changes caused by land cover/ land use properties and their impact on rainfall characteristics. Global J. Environ. Sci. Manage., 9(3): 353–372 **(20 pages)**.

USGS, (2019). Landsat 8 (L8) Data Users Handbook. LSDS-1574. Department of the Interior US Geological Survey.

Van der Laan, C.; Budiman, A.; Verstegen, J.A.; Dekker, S.C.; Effendy, W.; Faaij, A.P.C.; Kusuma, A.D.; Verweij, P.A., (2018). Analyses of land cover change trajectories leading to tropical forest loss: Illustrated for the West Kutai and Mahakam Ulu Districts, East Kalimantan, Indonesia. Land, 7: 108 **(19 pages).**

Varkkey, H.; Tyson, A.; Choiruzzad, S.A.B., (2018). Palm oil intensification and expansion in Indonesia and Malaysia: Environmental and socio-political factors influencing policy. For. Policy Econ., 92: 148–159 **(12 pages)**.

Ven, V.D.; Hamish; Rothacker, C.; Cashore, B., (2018). Do eco-labels prevent deforestation? Lessons from non-state market driven governance in the soy, palm oil, and cocoa sectors. Global Environ. Change. 52: 141–151 **(11 pages)**.

Williamson, J.; Slade, E.M.; Lukas, S.H.; Swinfield, T.; Chung, A.Y.C.; Cocomes, D.A.; Heroin, H.; Jucker, T.; Lewis, O.T.; Vairappan, C.S.; Rosster, J.; Strubig, M.J., (2020). Riparian buffers act as microclimatic refugia in oil palm landscapes. J. Appl. Ecol., 58(2): 431-442 **(12 pages)**.

Yanita, M.; Napitupulu, D.; Ernawati, H.D.; Fauziah, G.; Wahyuni, I., (2019). The performance of oil palm cultivation in Muaro Jambi District. IOP Conference Series: Earth Environ. Sci., 336: 012005 **(8 pages)**.

Zhao, J.; Elmore, A.J.; Lee, J.S.H.; Numata, I.; Zhang, X.; Cochrane, M.A., (2023). Replanting and yield increase startegies for alleviating the potentiol decline in palm oil production in Indonesia. Agric. Sys., 210: 103714 **(9 pages)**.

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CASE STUDY

Life cycle assessment of cocoa farming sustainability by implementing compound fertilizer

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ABSTRACT

BACKGROUND AND OBJECTIVES: The global competitiveness of the cocoa processing industry is enhanced through the implementation of technical policies as a sustainable economic sector. The effort is motivated by the potential of large cocoa production and the international market demands for the industry to apply innovative, effective technology and comply with sustainability standards (environment, social, and economic). Therefore, this study aimed to analyze the environmental impact assessment of cocoa production from upstream to downstream processes in North Luwu Regency, South Sulawesi.

METHODS: Data were collected from 321 respondents actively working and had at least 8 years of experience in cocoa cultivation and production. Respondents included staff of the Masagena Farmers' Cooperative from Chalodo Sibali Resoe Industry, Masamba City, and North Luwu Regency, and the secondary data were obtained from a literature review. In addition, the environmental impact was determined using the Midpoint Recipe method and the ecoinvent 3.8 database. This was conducted based on the International Standard Organization of life cycle assessment 14040 and 14044 with a function unit of 1 kilogram chocodate cashew production.

FINDINGS: The results showed that reducing chemical fertilizer was environmentally preferable to decreasing all the impact categories assessed since the total potential global warming impact from chocodate cashew production was 2.092 kilogram carbon dioxide equivalent. In this context, electricity and fertilizer were the main contributors to environmental pollution, accounting for 0.438 kilogram carbon dioxide equivalent and 0.215 kilogram carbon dioxide equivalent at 20.97 percent and 10.27 percent, respectively.

CONCLUSION: The reduction in the use of inorganic nitrogen, phosphate, potassium fertilizer, from 3.75 to 1.25 kilogram perkilogram cocoa, or the adoption of bio-based nitrogen, phosphate, potassium fertilizer at a rate of 2.5/ kilogram, could substantially mitigate the environmental impact. This mitigation resulted in a 16 percent decrease in global warming potential, reducing from 2.092 to 1.745 kilogram carbon dioxide equivalent. In addition, valuable insights were provided into the scope of life cycle assessment studies and contributed to the selection of sustainable cacao farming systems. These results could be relevant to life cycle assessment practitioners, stakeholders, and governments in offering valuable insights for the formulation of policies and programs for developing cacao farming in the future.

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INTRODUCTION

Indonesia is the world's largest processed cocoa producer, accounting for approximately 15 percent (%) of global chocodate consumption, and the fifth producer after Ivory Coast, Ghana, Nigeria, and Cameroon (Beg *et al.,* 2017). Cocoa bean production was 220,000 tonnes and 231,000 tonnes in 2019 and 2020, respectively. Cocoa represents a strategically important export commodity with the potential to yield substantial profits as an export commodity. In addition, it is a leading commodity in international trade, along with rubber, palm oil, and coffee. The large production capacity contributes as one of cocoa planting hearts, reaching 61.4% of the national cocoa area to the economy in all circumstances. Despite the impact of the coronavirus outbreak, cocoa processing industry continued to contribute to foreign exchange. This was evident in the export value of domestically processed cocoa products in 2020, which amounted to approximately 1.12 billion United States dollars (USD), marking an increase of 12% compared to the previous year (Parra-Paitan and Verburg, 2022). In addition to high production capacity, the products have a distinctive taste that increases their competitiveness in the global trade market. Processed cocoa products in the form of liquor, butter, powder, and cake are exported to large international markets including the United States, Netherlands, India, Germany, and China (Harya *et al*., 2018). Despite their high product competitiveness, the added value is still low, due to a relatively slow cocoa processing industry. This is affected by the low quality of production from smallholder plantations, namely 92.34% with a total of 1,400,636 micro, small and medium-sized enterprises (MSMEs) as producers (Tothmihaly *et al*., 2019). Cocoa production from farmers significantly contributes to the global value chain since it is exported to numerous countries. Similar to the exports from the agricultural and plantation sectors, efforts are needed to increase value-added products and maintain product competitiveness in the global trade market. The strategic and technical measures include enhancing crop productivity, elevating the quality of processed cocoa products, maintaining the policy of export duty tariffs for cocoa bean, enhancing infrastructure, and fostering a conducive and productive industry environment. Furthermore, it is important to be in line with the global market preferences, which increasingly demand environmentally friendly cocoa cultivation and processing methods. Compared to other agricultural products, cocoa liquor, butter, and powder have relatively low environmental impacts (2–4 kilogram carbon dioxide equivalent (kg CO_2-eq) (Misselbrook *et al*., 2000). Even though cocoa is a plantation crop with a relatively lower impact, it is crucial to address and mitigate its environmental footprint, considering the role as a food crop and staple source of sustenance for the Indonesian population. Beside greenhouse gas (GHG), cocoa production also presents significant emissions of ammonia (NH_3) and methane (CH_4) due to fertilizer use, with NH_3 emissions contributing to acidification (Fardet and Rock, 2020). Nitrous oxide (N_2O) and NH_3 must be addressed to minimize GHG emissions from cocoa production. This impact can be measured through a framework known as life cycle assessment (LCA) which characterizes and depends on the flow of input, output, energy, and emissions in the supply chain. Therefore, physical, social, and economic changes to the environment influence the interpretation of analysis results. Physical environmental impacts include measuring the soil potential of hydrogen (pH), implementing good agricultural practice (GAP), soil and air management technology, and types of plant varieties. In economic terms, farmers' management of essential production inputs, including fertilizer usage (Samimi *et al.,* 2023), the quantity of entries, specifications, labor allocation, and financial record-keeping in the industry, plays an important role. Concurrently, in the social context, the interplay between farmers is of great significance. This comprises their inclusion in group activities, community initiatives, and the pursuit of information regarding cocoa production enhancement through interactions with government agencies, corporations, and other pertinent stakeholders (Idawati *et al*., 2018; Idawati and Ariyanto, 2019; Recanati *et al*., 2018). The International Organization for Standardization (ISO) 14040-14044 provides guidelines for the design and execution of LCA studies. LCA method can identify and mitigate the main causal effects of the use of materials resulting in negative environmental impacts at all stages of the supply chain (Konstantas *et al*., 2018). Therefore, this study aims to investigate the environmental impacts of improved nitrogen fertilizer application in cocoa production, from cradle to grave (Ramos *et al*., 2022). The results may be used to improve the environmental sustainability of market-oriented cocoa production systems. The quantifiable benefits are the direct assessment of cocoa production systems to inform policymakers on regulation and environmental impact mitigation measures, assist farmers in implementing GAP, and educate consumers on the benefits of more sustainably produced goods (Bianchi *et al*., 2021; Santoso *et al*., 2023). The results have the potential to assist entrepreneurs in evaluating the viability of cacao production supply system, with a specific focus on identifying the variables influencing the systems. The analysis includes categorizing the effects of cocoa production on the global warming potential (GWP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), and acidification terrestrial potential (ATP) emissions. The objectives are: 1) assess the most significant environmental impacts and identify critical phases and hotspots, 2) compare the environmental performance of various production system modifications, and 3) propose methods to reduce negative environmental impacts and encourage more sustainably produced cocoa using LCA results. This study was carried out at the Masagena Farming Cooperative in Pongo Village and PT Chalodo Sibali Resoe Industry, Limited company (Ltd), Masamba City, North Luwu Regency, South Sulawesi Province, Indonesia, from 2022 to 2023.

MATERIALS AND METHODS

The total area of cocoa plantation in North Luwu Regency was 40,814.56 hectare (ha) and 38,367.04 ha in 2020 and 2021, respectively, operated by

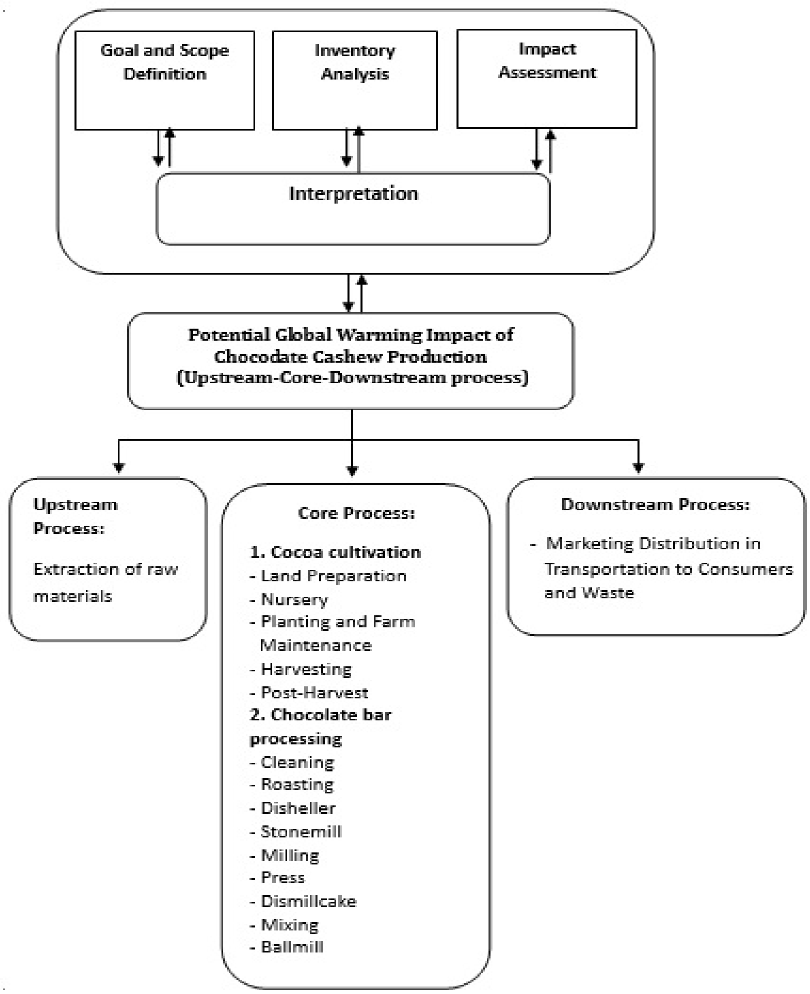

Fig. 1: Framework LCA stages of chocodate cashew production processes

29,481 heads of families and 26,567 farmers, with a production rate of 87.10 tons/ha. The number of farmers in 2021 was 26,567, with a total land area of 38,367.04 Ha. This analysis is a case study of the Masagena Farming Cooperative with a land area of 2,424 ha, owned by 1,616 active farmers. The calculation of the representative sample size from the total population of 1,616 using the Slovin formula is 321 farmers, as shown in Eq. 1 (Sevilla, 2007).

$$n = \frac{N}{1 + N * e^2} \quad (1)$$

Where; n is the number of samples, and N is the total population.

The method used adhered to the ISO 14040:2006 series LCA framework. The initial stage included determining objectives and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretive analysis of the potential global warming impacts of chocodate cashew production. The characterization results in Table 3 are presented based on the cases of (Rahmah *et al*., 2022), as shown in Fig. 1.

Study area

This study was conducted at the Masagena Farmers' Cooperative in the functional unit of 1 kg chocodate cashew from the total production in one harvest season (6 months/production) of Pongo Village and PT Chalodo Sibali Resoe Industry, Ltd., in Masamba City, North Luwu Regency, South Sulawesi Province, Indonesia, from October 2022 to September 2023 Fig. 2.

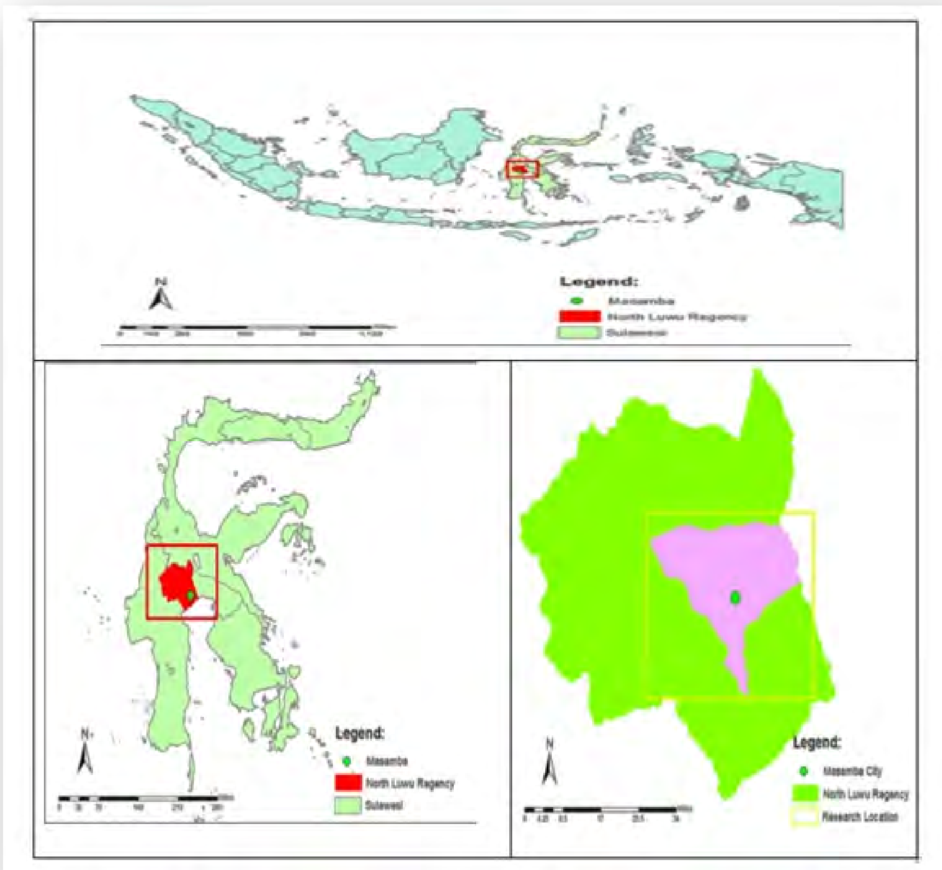

Fig. 2: Geographic location of the study area in Indonesia and detailed cocoa field study location

Table 1. Previously study GWP impact category for 1 kg chocodate production

No	Boundary	Unit faction	Total GWP (kg CO_2-eq)
1	Cradle to gate	1 kg of chocodate bar	1.65-4.21
2	Cradle to gate	1 kg chocodate, packed	2.1-4.1
3	Cradle to gate	1 kg chocodate	2.62
4	Cradle to gate	1 kg chocodate	7.3

Functional units

The functional unit was produced from the production process of 1 kg chocodate cashew production. This referred to the use of inputs and outputs of materials from the cultivation, processing, and transportation stages, LCI and LCIA stages (Permatasari *et al*., 2019). In this study, the standard results for calculating the impact of global warming are based on existing databases. The results were also compared to several previous studies (Busser *et al*., 2009; Rancanati *et al*., 2018; Boakye-Yiadom, *et al*., 2021; Dianawati, *et al*., 2023), as presented in Table 1.

Life cycle inventory (LCI) analysis

LCI is the second framework of LCA method which consists of recording several data from upstream to downstream used in the production process. These stages constitute activities ranging from the initial cultivation in the garden to the inclusion of the Masagena Farmers' Cooperative, subsequent processing in industry, distribution through retailers, and reaching the end consumers. The inventory analysis is divided into two stages, namely data collection and analysis (Waluyo *et al*., 2018). Primary data were obtained through field observation and interviews using a questionnaire on input and output materials. In this context, simple random sampling was used to obtain 321 farmers consisting of members of the Masagena Farmers' Cooperative, and 5 staff of PT Chalodo Sibali Resoe Industry Ltd., Masamba City, North Luwu Regency, as well as individuals included in the process of chocodate cashew production. Concerning the criteria for the survey, respondents were actively working and had at least 8 years of experience in cocoa cultivation and production. Meanwhile, LCI and environmental impact were determined using the ecoinvent 3.8 database and the Midpoint Recipe (H) method based on the ISO 14040 and 14044 standards. The base unit of function was selected as 1 kg chocodate cashew production.

The scope of analysis, shown in Fig. 3, includes cocoa cultivation (land preparation, nursery, storage and garden maintenance, harvesting, post-harvest), chocodate bar processing (cleaning, roasting, dispeller, stone mill, milling, press, dismillcake, mixing, ball mill), printing and packaging, marketing distribution, transportation to consumers, and waste (cradle to grave).

Data collection

The data collected covered the use of fertilizers, pesticides, granulated sugar, cashews, milk, packaging, transportation, and power generation. In this context, the data regarding land preparation consists of the use of gasoline, oil, application of compost, herbicides, and electricity. This is followed by the nursery which consists of seeds, soil, water, plastic polybags, UV (Ultraviolet) plastic for the roof, electricity, and the administration of organic fertilizer mixed with soil at cocoa nursery. The next stage of seed planting consists of input polybags, fertilizer using nitrogen phosphate kalium (NPK) fertilizer (inorganic fertilizer), herbicides in the weed cleaning process, fungicides functioning to control plant pest organisms (PPO) in cocoa plants, electricity use, and water. Cocoa plant maintenance requires NPK fertilizer, liquid organic fertilizer, insecticides, herbicides, fungicides, water, and gasoline. The harvest and post-harvest stages include the use of plastic sacks/bags and gasoline, followed by the harvest transportation to the farmers' house or to the location where the wet cocoa bean is purchased. Subsequently, the process of fermentation and drying of the seeds comprises the use of sunlight with a UV plastic roof, paranet mats (simple greenhouse), plastic sacks/bags, wooden boxes, and banana leaves covering the boxes. Table 2 shows the results of the inventory analysis from the input-output system in cocoa production process, including pre-harvesting and harvesting. Cocoa bean processing consists of sorting, roasting, and deshelling skin from the

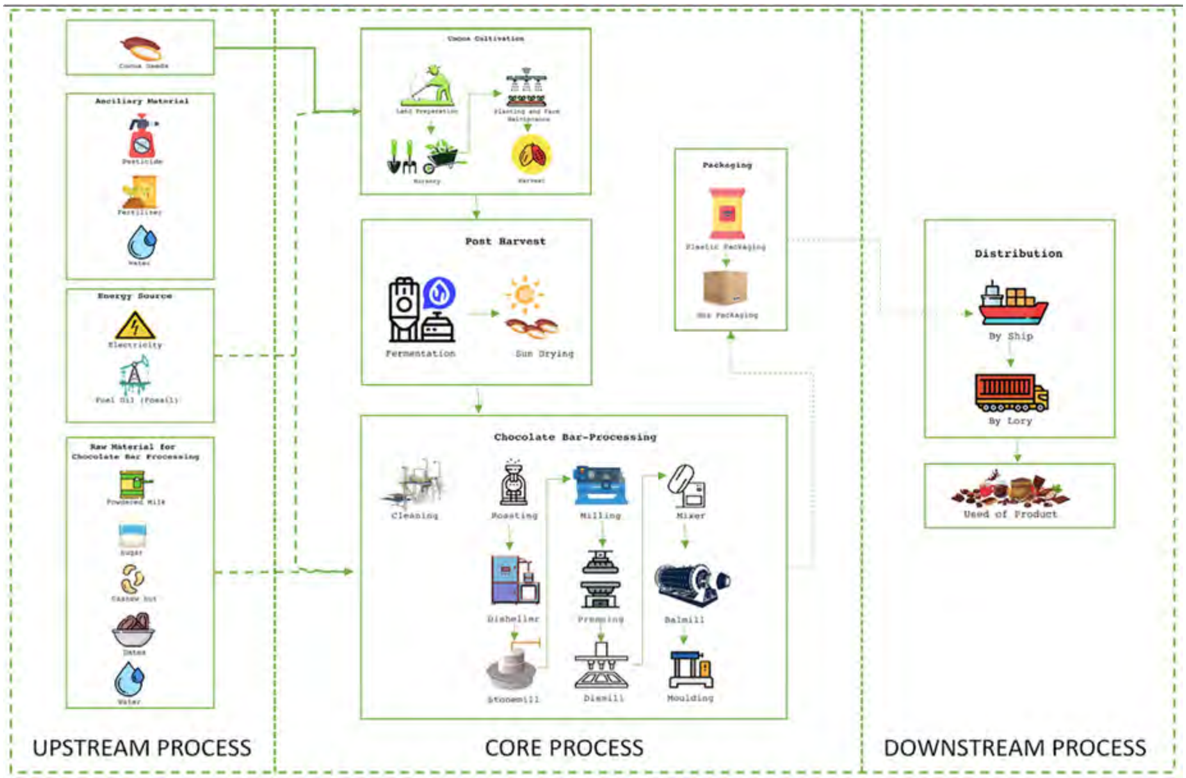

Fig. 3: System boundary of chocodate cashew production processes

nibs using a plastic bag container, LPG (Liquefied Petroleum Gas), and electricity, respectively. The obtained nibs are converted into a coarse paste using a stone mill and electricity, which is then refined in a milling machine to produce liquor. Furthermore, the liquor is pressed to separate cocoa butter and cake. In the next stage, the cake is mashed in a dismillcake machine to produce cocoa powder which is mixed with several additional ingredients to make the final chocodate paste product. This paste is fed into the ball mill to produce a ready-to-mold paste which is put in a cooler before molding into the final products, such as chocodate cashew. Subsequently, cashew is packaged using several layers of packaging before distributing. The main data are the source of cocoa bean (the distance from the Masagena Farmers' Cooperative to the industry), types, sources, and transportation related to the distribution of purchases of materials such as sugar, cashew nuts, milk, and others. Table 3 shows the electricity and water usage as well as the packaging materials.

Data analysis

The collected data were translated into values related to functional units. The adjusted data were entered using the Midpoint Recipe (H) 2016 method and aggregated to produce inventory tables (Muñoz *et al*., 2014).

Life cycle impact (LCI) assessment

Inventory analysis was carried out to calculate the possibility of environmental impacts by identifying the input and output materials used (Caicedo-Vargas *et al*., 2022; Ntiamoah and Afrane, 2008). The stages of measuring the environmental impact of using organic fertilizer on cocoa production are carried out in stages.

1. Due to the limitations of the organic fertilizer dataset, the material input process uses analytical laboratory data information.
2. Information on the composition of organic fertilizer was gathered and calibrated according to the emission factors sourced from the relevant database.

Table 2: Inventory data of the input and output of cocoa cultivation

Unit process	Material	Unit	Amount/6 months production	Amount/1 kg production
Land preparation input	Land use	ha	1	0.002
	Compost	kg	4,500	9
	Gasoline	L	10	0.02
	Herbicide	L	10	0.02
	Lubricant	L	10	0.02
	Groundwater	L	51,000	102
	Plastic bag	kg	15	0.03
Output	Land use	ha	1	0.002
	Herbicide bottle	kg	0.5	6.94E-06
	Lubricant bottle	kg	0.02	2.78E-06
	Waste lubricant	L	0.02	2.78E-06
Nursery input	Land use	ha	1	0.002
	Cocoa tree	tree	650	1.3
	Soil	kg	800	1.6
	Groundwater	L	1,600	3.2
	Polybag plastic/satellite super	kg	1,500	3
	Roofing plastic/UV/polycarbonate	kg	35	0.07
	Electricity	L	100	0.2
	Liquid an-organic fertilizer	kWh	0,05	6.94E-06
		kg	2	0.004
Output	Cocoa tree	tree	625	1.25
	Polybag plastic	kg	775	1.55
	Roofing plastic	kg	5	0.01
	Liquid an-organic fertilizer	kg	25	0.05
	Plastic	kg	0.25	3.47E-05
Planting and Farm Maintenance input	Cocoa tree	tree	610	1.22
	Nitrogen	kg	1,875	3.75
	NPK Phosphorus	kg	1,875	3.75
	Potassium	kg	1,875	3.75
	Organic fertilizer	kg	900	1.8
	Liquid organic fertilizer	kg	36	0.072
	Herbicide	kg	32	0.064
	Fungicide	kg	15	0.03
	Insecticide	L	15	0.03
	Irrigated water	L	100,000	200
	Gasoline	L	100	0.2
Output				
	Cocoa tree	tree	605	1.21
	NPK Phonska Plastic	kg	10	0.02
	Organic fertilizer plastic	kg	3	0.006
	Liquid organic fertilizer Plastic	kg	8	0.016
	Herbicide bottle	kg	3	0.006
	Fungicide bottle	kg	1	0.002
	Insecticide bottle	kg	1	0.002
Harvesting input	Cocoa tree	tree	600	1.2
	Wet cocoa bean	kg	1,400	2.8
	Plastic bag	kg	0.5	6.94E-06
	Gasoline	L	30	0,06
Output	Wet cocoa bean	kg	1,350	2.7
	Plastic bag/polypropylene	kg	0.5	0.001
	Gasoline	L	30	0.06

Continued Table 2: Inventory data of the input and output of cocoa cultivation

Unit process	Material	Unit	Amount/6 months production	Amount/1 kg production
Transportation to fermentation Input	Wet cocoa bean	kg	1,400	2.8
	Plastic bag	kg	0.4	5.56E-06
	Gasoline	L	26	0.052
Output	Wet cocoa bean	kg	1,400	2.8
	Plastic bag /polypropylene	kg	0.4	5,56E-06
Fermentation Input	Wet cocoa bean	kg	1,400	2.8
	Wood fermentation	kg	50	0,1
	Banana leaf	L	0.2	2,78E-06
	Plastic bag	kg	0.5	6,94E-06
Output	Wet cocoa bean	kg	1,300	2.6
	Plastic bag /polypropylene	kg	0.5	6.94E-06
Drying input	Wet cocoa bean	kg	1,250	2.5
	Plastic UV	kg	0.7	9.72E-06
	Paranet mat	kg	4	0.008
	Plastic bag	kg	10	0.02
Output	Dry cocoa bean	kg	550	1.1
	Plastic bag /polypropylene	kg	18	0.036
Transportation to manufacturing	Dry cocoa bean	kg	500	1.1
	Plastic bag	kg	0.2	1
	Gasoline	kg	26	2.78E-06
Output	Dry cocoa bean	kg	500	1
	Plastic bag /polypropylene	kg	0.2	0.0004

The ISO 14040 guidelines show that there are four optional elements, namely normalization, scoring, clustering, and data quality analysis. This guide applies the results of inventory data to classify and characterize potential environmental impacts. In this context, the classification and characterization using mandatory elements are considered to be sufficient to achieve the stated objectives. According to (Armengot *et al.*, 2021), in the classification stage, generating the inventory data from the calculation results is performed by multiplying the relevant emission mass value. This is achieved by the appropriate characterization factor provided by the ecoinvent 3.8 databases to produce the indicator results for inventory items. The impact category is the impact score or characterization results obtained from the sum of the indicators in each category. In this study, the characterization obtained is grouped into environmental impacts of freshwater ecotoxicity potential (FEcP), human carcinogenic toxicity (HCP), freshwater eutrophication potential (FEP), ozone depletion potential (ODP), human non-carcinogenic toxicity potential (HnCT), water scarcity (WS), terrestrial acidification potential (TAP), global warming potential (GWP), marine eutrophication (MEP), land use potential (LUP), ozone depletion potential (ODP), and mineral resources scarcity (MRS).

Study limitations

The scope of this study is restricted to North Luwu Regency, South Sulawesi Province, Indonesia. Therefore, it is not possible to generalize the results to the entire country. In this context, the expansion of the scope to include other cocoa production locations is a valuable prospect for future investigations. In this technical assessment, there are several limitations:

1. The characterization factor of the material is not found in available databases, hence, the value is adjusted by the characterization factor from the dominant constituent materials.
2. All infrastructure and equipment that supports cacao production are not included in impact calculations.
3. The transportation data used are the result of accommodation with the sharing loading method.

Table 3: Inventory data of the inputs and outputs of cocoa processing

Unit Process	Material	Unit	Amount/6 month production	Amount/1 kg production
Cleaning input	Dry cocoa bean	kg	450	0.9
	Plastic bag/polypropylene	kg	0.1	1.39E-06
Output	Dry cocoa bean	kg	450	0.9
Roasting input	Dry cocoa bean	kg	450	0.9
	LPG Dutching-Alkaline	kg	3	0.006
Output	Roasted cocoa bean	kg	449	0.898
Desheller input	Roasted cocoa bean	kg	449	0.898
	Electricity	kWh	840	1.68
	Shell/husk	kg	20	0.04
Output	Nibs	kg	429	0.858
Stonemill input	Nibs	kg	429	0.858
	Electricity	kWh	820	1.64
Output				
	Coarse pasta	kg	427	0.854
Milling input	Coarse pasta	kg	427	0.854
	Electricity	kWh	320	0.64
Output	Cocoa liquor	kg	420	0.84
Pressing input	Cocoa liquor	kg	420	0.84
	Electricity	kWh	240	0.48
	Cocoa Butter	kg	110	0.22
Output	Cake	kg	310	0.62
Dismillcake input	Cake	kg	310	0.62
	Electricity	kWh	600	1.2
Output	Cocoa powder	kg	300	0.6
Mixing input	Cocoa powder	kg	300	0.6
	Powdered milk	kg	3	0.006
	Sugar	kg	3	0.006
	Vanilla	kg	0.7	9.72E-06
	Lecithin	kg	0.5	6.94E-06
	Cashew nuts	kg	2.2	0.000169
	Dates	kg	1.2	8.61E-05
	Water	L	5.0	0.000417
	Electricity	kWh	340	0.68
Output	Brown fat	kg	70	0.14
	Chocodate paste	kg	400	0.8
Ballmill input	Chocodate paste ready to print			
	Electricity	kg	400	0.8
		kWh	100	0.8
	Chocodate paste ready to print			
Output		kg	400	0.2
Moulding input	Chocodate paste ready to print	kg	400	0.8
	electricity	kWh	100	0.2
Output	Chocodate cashew	kg	408.6	0.817
Packaging input	Chocodate cashew	kg	408,6	0.817
	Metallic paper	kg	0.001	0.000002
	Parchment paper	kg	0.01	1.39E-06
	Wire tape	kg	0.002	0.000004
	Stand pouch	kg	0.02	2.78E-06
	Plastic bag	kg	0.1	1.39E-06
	Cardboard box	kg	0.5	6.94E-06
Output	Chocodate cashew	kg	500	1

RESULTS AND DISCUSSION

The characterization results obtained in this study are presented in Table 4. In this context, the global warming potential and the land use potential are 2.092 kg CO_2-eq, 2.084 kg 1,4-DCB (Dichlorobenzene), and 1.102. The amount of square meter (m^2) of change of land cover square meter of change of land cover (m^2a crop eq).

The environmental impact is described by the relative contribution of each studied life cycle stage as shown in Fig. 4. The largest relative contribution in cocoa cultivation stage is LUP, MEP, MRS, ODP, and WS at 82%, 79.5%, 78.8%, 78%, and 77.8%, respectively. The largest and similar stages of chocodate bar processing are Marine ecotoxicity potential (MEcP) at 88%, Freshwater eutrophication potential (FEP), Ionizing radiation (IR), Human carcinogenic toxicity (HCT), and GWP at 67%. At the post-harvest stage, the

Table 4: Characterization results for 1 kg chocodate cashew production

Environmental impact category	Total impact score	Unit
Marine ecotoxicity	0.124	kg 1,4-DCB
Freshwater ecotoxicity potential	0.101	kg 1,4-DCB
Human carcinogenic toxicity potential	0.086	kg 1,4-DCB
Human non-carcinogenic toxicity potential	2.084	kg 1,4-DCB
Terrestrial ecotoxicity	6.812	kg 1,4-DCB
Freshwater eutrophication potential	0.001	kg P eq
Fossil resource scarcity	0.467	kg oil eq
Ozone formation, terrestrial ecosystem	6.812	kg NOx eq
Ionizing radiation	0.204	kBq Co-60 eq
Ozone formation	0.007	kg NOx eq
Water scarcity potential	0.093	M^3
Terrestrial acidification potential	0.012	kg SO_2 eq
Global warming potential	2.092	kg CO_2 eq
Fine particulate matter formation	0.005	kg $PM_{2.5}$ eq
Marine eutrophication potential	0.001	kg N eq
Land use potential	1.102	m^2a crop eq
Stratospheric ozone depletion potential	7.10454E-06	kg CFC11 eq
Mineral resource scarcity potential	0.001	kg Cu eq

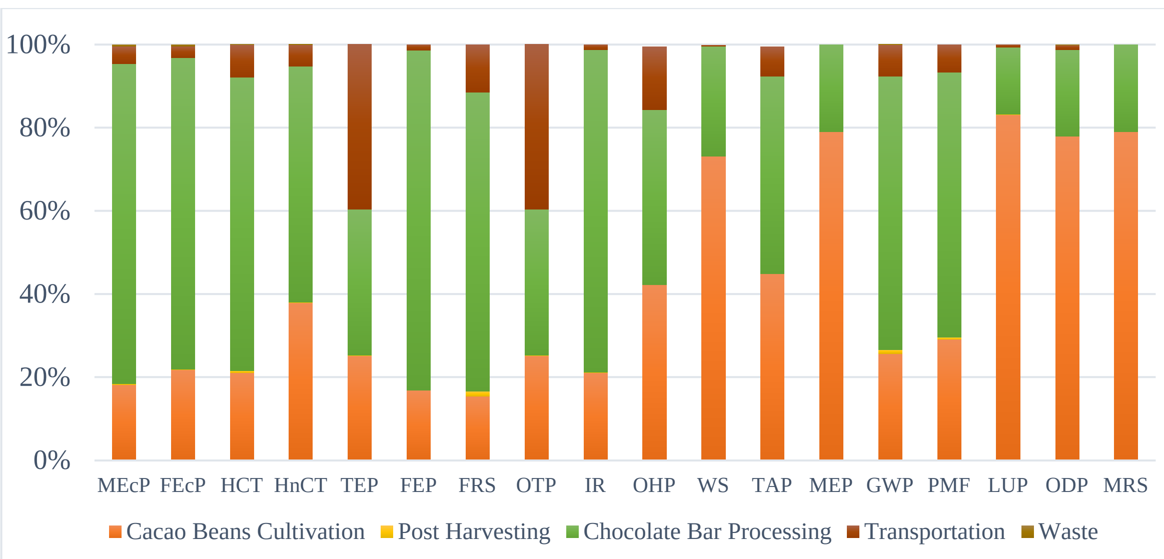

Fig. 4: Contribution by different production stages to the overall environmental impact score

scarcity of fossil resources scarcity (FRS) is very small, and at the transportation stage, the biggest source of environmental impacts is the formation of ozone, terrestrial ecosystems, and Terrestrial ecotoxicity potential (TEP) at 38%.

LCA can present a more comprehensive picture of the environmental impact of a product or activity through the results of combining the weighing and normalization stages. This enables decision-makers to prioritize and direct improvement efforts or mitigation stages to address the most significant environmental impacts to realize more sustainable products or activities. According to Fig. 5, the impact assessment of the life cycle normalization of cocoa production with the largest environmental impact is MEcP, followed by FEcP, with LUP the third lowest after ODP.

Cocoa cultivation stage

The stages of cocoa bean cultivation consist of land preparation, nursery, garden planting and maintenance, harvesting, and post-harvesting. Fig. 4 shows that the environmental impacts have the highest average distribution at cocoa bean cultivation stage, particularly LUP, MEP, MRS, ODP, and WS is 77–82 %, while at the very small post-harvesting stage the impacts are due to from FRS. The results of the analysis indicate that the highest environmental impact is at cocoa cultivation stage, namely LUP at 82%, where land use with one type of NPK fertilizer is the main cause of the environmental impact at the production stage of 0.215 kg CO_2 eq or 10.27%. The use of NPK fertilizer at the stage of maintaining the garden contains several nutrients needed by plants with high levels of N, P, and K (inorganic fertilizers). This is achieved by physically mixing three quality raw materials which include urea granules, diammonium phosphate granules (DAP)/$(NH_4)_2HPO_4$, and Potassium chloride (KCL) flakes (Albaugh *et al.*, 2021). The global warming potential is due to the fertilization process as the main concern regarding environmental impacts. In this context, phosphate emission is the main contributor to heavy metals from the production of P contained in NPK fertilizer at the cultivation stage. Therefore, improvement measures must be focused on reducing the use of fertilizer to design a sustainable cocoa industry (Suh and Molua, 2022). These measures should be implemented with minimal resource input to preserve limited resources, and manage waste, water, and soil pollution (Armengot *et al.*, 2021; Ratnawati *et al.*, 2023). Other beneficial approaches include using compost, avoiding the use of chemicals, enhancing integrated pest management through the right plants, and implementing efficient

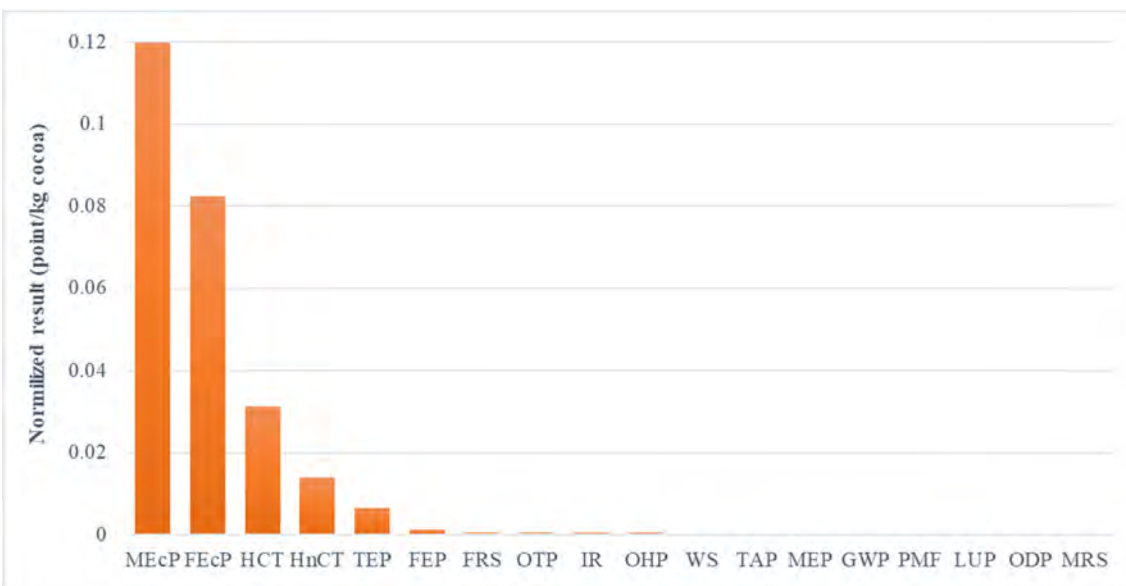

Fig. 5: Life cycle impact assessment normalization of cocoa production

irrigation and xeriscaping. This effort is closely related to the technical ability of farmers in adopting GAP to provide farmers with an understanding of the dependence of cocoa plant on climatic elements, such as rainfall fluctuations, availability of quality infrastructure, soil management to reduce land degradation, nutrient balance, resource capacity to access environmentally friendly technology (Idawati *et al*., 2023). The use of agricultural machinery and equipment in cocoa production remains quite rudimentary and labor-intensive. This is attributed to the small-scale nature of the plantations, typically ranging from 1 to 2 ha/farmer, and the heavy reliance on rainfall for production. The drying of cocoa bean is managed at the Masagena Farmers' Cooperative, using a basic greenhouse system where sunlight serves as the primary source for the drying process. Therefore, improvement measures must be focused on constructive and vegetative methods through government, private, and community policies as well as land use depending on suitability and cost requirements. These actions should be regulated by spatial policies and market forces through landscape configuration, agricultural location, and intensification of practices by reducing the use of chemicals and introducing organic fertilizers (Mugiyo *et al*., 2021). An essential impact during cocoa cultivation stage is the substantial generation of solid waste post-harvesting. Specifically, the accumulation of cocoa pod shell in large quantities merits significant attention and consideration (Walkiewicz *et al*., 2021). Approximately 67% of the weight of fully ripe cocoa pod is composed of the fruit skin. Among the environmental impacts, cocoa pod shell waste is not assessable through LCA method. Therefore, it becomes important to manage this waste by implementing processes such as garden sanitation, as recommended in GAP, in line with the principles of sustainable agriculture. Furthermore, solid cocoa pod shell waste can be converted into a liquid form, which serves as valuable compost and even be commercialized. An innovative application for cocoa pod shell waste includes its transformation into charcoal briquettes, presenting a relatively recent alternative energy source at the household level. This multifaceted approach addresses waste management and contributes to sustainable practices as well as alternative energy solutions (Duan *et al*., 2020). Charcoal briquettes are produced from burning cocoa pod shell and can be an alternative energy source produced on a household scale. These materials can be a source of C and N used by microbes in the soil through the decomposition process during the rainy season to reduce CO_2 emissions. In this context, land use and the presence of drainage channels cause an increase in CO_2 emissions due to a decrease in the groundwater level. Therefore, increased oxygen levels accelerate the process of decomposition of organic matter in the soil. This effect occurs when the process of litter by soil microorganisms decomposes and can become a source of organic matter in the soil (Nuriana and Anisa, 2014). This method should be followed by more farmers to minimize the dependence on chemical fertilizer. Meanwhile, important environmental issues are land degradation and loss of biodiversity due to excessive use of fertilizer by farmers. The monoculture system applied with the same cocoa clones reduces or eliminates the diversity of natural flora and fauna as an effort to balance the ecosystem through the application of agroforestry system (Akrofi-Atitianti *et al*., 2018). This system establishes native vegetation such as forests by combining plants with plantations and replacing chemical pesticides with more environmentally friendly biopesticides.

Cocoa processing stage

Cocoa or chocodate bar processing stage has the most significant environmental impact on MEcP, FEcP, WS, MEP, and LUP. Furthermore, it has the largest contribution to FEP and FEcP at 27.21% and 24.78%, and in electricity usage which is the main cause of the environmental burden at 0.438 kg CO_2 eq, or 20.97%. Electricity usage was identified as the main environmental impact contributor at PT Chalodo Sibali Resoe Industry Ltd., in the manufacturing of chocodate cashew (Perez *et al*., 2021). Therefore, it is important to enhance the efficacy of electrical energy use in the energy-intensive apparatus. In this context, there is a suggestion to substitute the utilization of electricity with natural gas due to the recognized comparative environmental friendliness. The derivative of the processing sector, namely cocoa shell/husk, has transformed in its classification from solid waste to a marketable commodity, after processing and packaging procedures (Barišić *et al*., 2020).

Marketing distribution stage

The marketing distribution and transportation stage has an environmental impact with a low contribution to the category. The effects of transportation on consumers consist of FEP, ODP, HnCT, TAP, and GWP, and the biggest impact on waste is HCT. The transportation stage includes transportation to consumers as the most relatively environmentally friendly because the category of impact is not considered significant. This is because the marketing process outside Masamba City has not been optimal and the production is on a small scale.

Improvement analysis

Modifications are offered as models and improvement options for reducing potential environmental impacts. The base case of cocoa cultivation, cocoa processing, and transportation is in North Luwu Regency, and the proposed improvement options are presented in Table 5. From the results of the environmental impact analysis of the three stages, the biggest impacts are GWP and LUP. Therefore, improvement options can be recommended using the improvement analysis, to determine the calculation of different scenarios by analyzing the effect of input parameters on the LCIA output. The sensitivity analysis for environmental impacts was applied for the use of fertilizers at cocoa cultivation stage.

The impact of changing scenarios on GWP and LUP is presented in Fig. 6. The results show that by changing the input of Phonska NPK fertilizer (Inorganic fertilizer) to be more efficient, GWP decreases to 1.745 kg CO_2 eq. Changes in GWP through the level of fertilizer input in the design of an information system have a more significant effect on the results of the environmental impact characterization compared to the base case using NPK fertilizer. Therefore, a high percentage of NPK affects the GWP impact through N_2O emissions compared to synthetic or organic fertilizer, manure, plant straw, and waste output. In this context, the use of high chemical inputs is significant for a high GWP. The analysis shows a significant issue with fertilizer usage, with a rate of 3.75/kg of cocoa. Therefore, fertilizer use needs to be reduced to 1.25/kg which leads to a reduction in GWP from 2.09 to 1.745 kg CO_2-eq.

The use of compound (NPK) fertilizer on cocoa provides a very complex response and requires an

Table 5: Proposed improvement options

Life cycle stage	Base case	Proposed improvement options
Cocoa production	NPK fertilizer (compound fertilizers) based on petrochemicals	1. Reduction of petrochemical-based NPK fertilizer (compound fertilizer) 2. The use of bio-based NPK fertilizer (compound fertilizer)

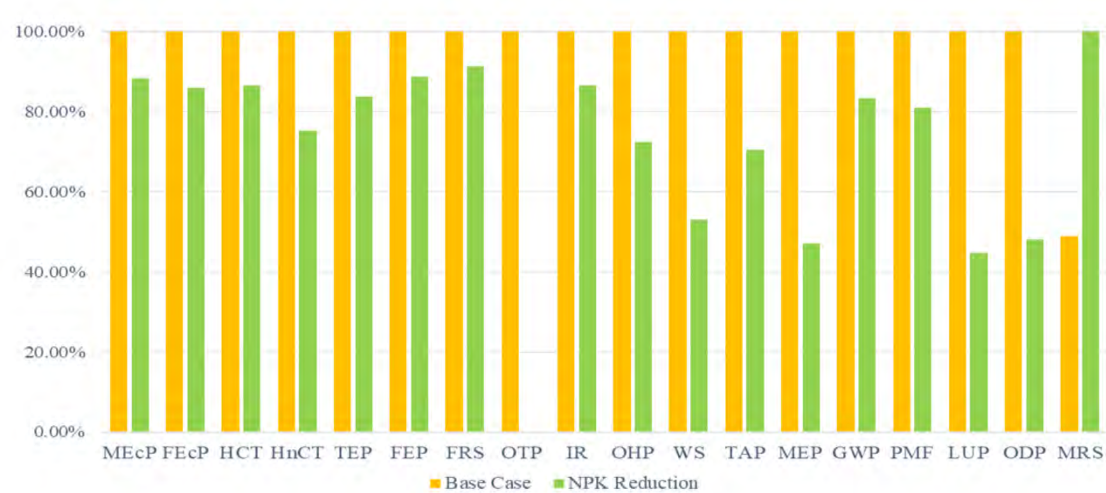

Fig. 6: Comparison of potential environmental impacts between the base case using NPK fertilization and the assumed case of reducing NPK fertilization for cocoa production stage.

optimal fertilization strategy to transmit various land suitability criteria to eliminate cocoa. The results of (Singh *et al*., 2021; Amponsah-Doku *et al*., 2022) provide information that variations in response to the use of cocoa fertilizer are caused by rainfall, slope, and soil conditions, composition, type, and time of fertilizer application. Therefore, it is necessary to recommend the right type of fertilizer, dose, and time to increase the productivity, and longevity of cocoa plants, reduce ecological restoration of the soil, and increase the cost-benefit ratio of fertilization. According to Doe *et al*., (2022), there has been ecological restoration of cocoa agricultural soils, specifically in organic carbon (OC), pH, iron (Fe), and Aluminium (Al). In this context, it is necessary to improve OC and soil pH conditions while trying to adjust Fe and Al levels to Sustainable cocoa farming in Ghana. The fertilization mechanism evaluated constitutes a significant concern related GWP. Furthermore, this study assessed the emissions resulting from the decomposition of cocoa pod shell when incorporated into the soil as part of the composting process. The results indicate that the release of CH_4 and N_2O in the biodegradation process depended on the specific composting technology used and the duration of time. Approximately 8.50 kg of cocoa pod shell yield 1 kg of cocoa. The residual matter remaining in the soil has the potential to generate 2.60 kg CH_4 and 4 gr N_2O, equivalent to 7.69 kg CO_2 eq. Furthermore, the process of composting the waste resulted in the release of 34 grams of CH_4 and 2.55 g of N_2O. These emissions together equal a contribution of 1.61 kg CO_2 eq. In this context, the approach has the potential to decrease the carbon footprint (CF) associated with cocoa production by 6 kg CO_2 eq. The process of immersing cocoa pod shell into the soil has a significant effect on the CF due to the emissions from the anaerobic breakdown of organic waste. These account for approximately 85% of the total emissions observed in the two technologies examined. The result supports the need for action in making decisions regarding the mitigation of GHG emissions. Organic fertilizer is potential viable solution for minimizing the negative environmental impacts linked to GAP (Nemecek *et al*., 2011). The high impact besides the GWP is the LUP of 1.102, decreasing to 0.492 m^2a crop eq from the basic case applied by farmers (Fig. 6). Currently, LUP is the leading cause of biodiversity decline worldwide. Various land use categories have been evaluated for the effects of change, and different intensities due to sustainability of food, livestock, and processed wood production (Accatino *et al*., 2019). According to (Alkemade *et al*. 2009); Bellard *et al*. (2012), the impact of global warming shows a direct correlation with the increase in sea surface temperatures, which can hinder the proliferation of phytoplankton and affect mean species abundance (MSA) as well as the native species in the future. This phenomenon is anticipated to yield varying responses to escalating global average temperatures, exerting differential effects on biomes and species groups across distinct regions. The result indicate that environmental impacts are vulnerable to changes in the amount of material inputs and outputs. In this context, the use of NPK fertilizer is associated with a substantial environmental impact, with the most consequence being a significant escalation in the impact of climate change on MSA of indigenous species. This outcome is anticipated to yield distinct responses to the rising global average temperatures within various biomes and among different species groups across diverse regions. The results indicate that environmental impacts are vulnerable to changes in inputs and outputs. Agricultural landscapes in tropical drylands aim to create future groundwater and food security, as well as energy availability through land conservation management. This include restoration of degraded ecosystems, increased agricultural diversification, and individual initiatives at larger spatial scales (Soulsbury *et al*., 2021). In this context, it is necessary to apply a sustainable cocoa agroforestry landscape design with an energy-saving concept in a spatial and regional arrangement with a pattern of placement of trees and air spaces. This sustainable landscape should be developed with soil management strategies such as compost production and plantation waste handling to maintain and enhance healthy soil, support the diversity of soil life, as well as integrate renewable energy technologies (Santeramo and Lamonaca, 2021). Despite the inherent constraints associated with the use of LCA method in developing nations, the valuable environmental insights provided should be considered. The methods enable the identification of important environmental concerns and can facilitate the implementation of sustainable solutions. This case study has proven successful in measuring and identifying several important impacts related to the upstream-to-downstream cocoa production process (Sasongko *et al*., 2018). Sustainable cocoa production, commencing at the upstream stage, includes a series of measures. These initiatives begin with land preparation and extend to the reduction of bio-based inorganic fertilizers and pesticides. Furthermore, the adoption of cocoa agroforestry practices, which integrate productive shade crops, plays an important role. The sustainable practices enhance both cocoa cultivation and provide additional income streams for farmers. Furthermore, cocoa industry can consider using a full electricity network with the use of photovoltaics (PV) as an energy source (Rosmeika *et al*., 2023). The use of PV as an energy source in electric vehicles that use a full network has reduced the environmental impact significant to GWP, FEP, ODP, POFP, and TAP. A study conducted in Columbia made a significant contribution to the environmental impact caused by the assessment of the life cycle of cocoa production. In this context, the production with a composting system carried out in handling cocoa pod shell waste by immersing in the soil or rotting outside can be a source of emissions. However, these emissions cannot be predicted precisely because of the different management systems for cocoa plantations. The difference depends on the treatment of farmers based on crop needs, number of family dependents, soil conditions, type and dosage of chemical fertilizers, need for future demand for food products, as well as other considerations such as energy consumption from CO_2 emissions (Cheng *et al*., 2011). According to (Ortiz-Rodríguez *et al*., 2016), the potential for global warming emissions from cocoa plantations in Colombia produces 2–4 kg CO_2 eq/kg cocoa. Therefore, a way to achieve a constant level of reduction in N_2O emissions is to maintain the use of balanced fertilization doses. The application of agroforestry landscape systems and conventional management has an environmental impact measured in GWP kg CO_2-eq/ kg of the same magnitude, even though the impact may be lower (Schreefel *et al*., 2020). (Asitoakor *et al*. 2022; Sassen *et al*., 2022) show that the agroforestry system is an effort to conserve biodiversity and provide ecosystem services since P is available in the soil around cocoa plants. This level of productivity can be attained when shade trees are incorporated, resulting in higher yields compared to cocoa plant cultivated without such trees. A sustainable approach to food systems, which emphasizes the augmentation of production and consumption, must be obtained with the ecological surroundings. This includes the establishment of a circular food system, with the overarching goal of advancing global food security by minimizing external inputs carrying adverse environmental impacts. In this context, this current study aims to protect natural resources by closing the cycle of nutrients and carbon in circular food systems (Sasongko and Pertiwi, 2023). Regenerative agriculture is an approach that promotes soil and water conservation by applying cocoa agroforestry landscapes. This improves the quality management of agricultural land by implementing rehabilitation and revitalization of the entire ecosystem and contributing to various ecosystem services. The concept of cocoa agroforestry landscapes, which includes mixed cropping systems in a single land area is a significant catalyst for global environmental change. This approach adds economic value and bears responsibility for a substantial portion of total greenhouse gas emissions. The outcomes are achieved through the promotion of agroecosystem diversity and the integration of comprehensive environmental management practices (Sgroi, 2022). According to (Schroth *et al*., 2016), a mixed cropping system contains a variety of forestry crops (teak, pepper, dogfruit, cloves), fruits (durian, rambutan, mango, etc.), short-term crops (banana, papaya, cassava, corn, patchouli), medicinal plants, and farm animals such as chickens. This system includes cocoa land with a planting density of 4×4 m^2 which provides many ecosystem benefits, such as climate mitigation, carbon sequestration, biodiversity, nutrient cycling, and maintenance of soil fertility. Cocoa agroforestry is a sustainable forest intensification and protection policy implemented in the plantation landscapes as the key to environmental sustainability. Cocoa agroforestry with Melina trees (*Gmelina arborea*) is an alternative approach when there is a decrease in cocoa yields due to plant age. This reduces the impact of agricultural production systems, increases farmer productivity and income, reduces CO_2 emissions, and increases carbon sequestration (Ballesteros-Possú *et al*., 2022; Udawatta and Jose, 2011). Some relevant environmental impacts due to cocoa production include GWP and LUP, such as loss of biodiversity and the need for soil management due to the excessive use of chemical fertilization (Gaidajis and Kakanis, 2020; Rahmah *et al*., 2022).

CONCLUSIONS

In conclusion, fertilizer use during the cultivation stage of chocodate cashew production was reported to directly impact GHG emissions. This made a significant contribution to MEP due to the N and P derivatives contained in NPK fertilizer. LCA results focused on considering environmental elements and consequences as a tool used to plan sustainable development, explaining the principles, methods, and benefits to policymakers and decision-makers. In this context, this study represented one of LCA analysis conducted in cocoa industry, particularly in South Sulawesi. The objective of implementing the method was to measure the potential environmental impacts of cocoa cashew produced by PT Chalodo Sibali Resoe Industry. Furtehrmore, LCA was carried out to build a scientific basis for analyzing improvements in production sustainability. An assessment was conducted on the life cycle sustainability of cocoa farming by applying compound fertilizer at various stages of chocodate cashew production process. The results showed that reducing the use of chemical fertilizers was better for the environment to reduce the categories of impacts assessed. In this context, the total potential global warming impact from chocodate cashew production was equivalent to 2,092 kg CO_2. The main contributors to environmental pollution were electricity and fertilizer which contributed 0.438 kg and 0.215 kg CO_2-eq at 20.97% and 10.27%, respectively. The largest relative contribution at cocoa cultivation stage was LUP at 82%, followed by MEP, MRS, ODP, and WS at 80%. Chocodate bar processing stages are MEcP at 88%, FEP, IR, HCT, and GWP at 67%. At the post-harvest stage, FRS was very small but at the transportation stage, the largest impact contribution was ozone formation, land ecosystems, and TEP potential at 38%. Based on input in sequence, electricity and fertilizer contributed 0.438 kg CO_2-eq (20.97%) and 0.2148 kg CO_2-eq at 20.97% and 10.27%, respectively.

RECOMMENDATIONS

North Luwu Regency = is one of the largest cocoa producers in Indonesia. For the development of internationally competitive and sustainable products, it is important to understand the importance of industrial development, focusing on economic and social aspects and their impact on the environment. The following recommendations are possible:

1. Environmentally friendly: The improvement analysis shows that by reducing the application of inorganic fertilizer, specifically by decreasing the usage of potassium nitrogen phosphate from 3.75 to 1.25/kg cocoa, or by transitioning to vegetable-based potassium nitrogen phosphate at a rate of 2.5/kg, it is possible to significantly mitigate the environmental impact. This reduction amounts to approximately 16%, leading to a decrease in the global warming potential from 2,092 to 1,745 kg CO_2-eq.
2. Reducing the use of NPK fertilizer and replacing with environmentally friendly organic fertilizer. Recommended organic fertilizer includes compost, bokasi, petrogenic, and several liquid organic fertilizers for cocoa plant used to reduce chemical fertilizers. Furthermore, there are recommendations for fertilizer other than Phonska NPK, namely Rainbow NPK and the need to use lime to reduce the soil dryness.
3. Economically: The augmentation of cocoa agricultural production can be achieved by adopting agricultural practices rooted in regenerative and circular principles. This includes the provision of organic inputs and the integration of diverse varieties of cocoa clones in a single cocoa agroforestry landscape system.
4. Socially: The capacity of farmers can be increased through counseling and training in the manufacture and use of organic fertilizer.
5. Science and technology: The data collection can be used for comparison in future studies. Further analysis is needed regarding alternative electricity sources for cocoa industry, ranging from fossil fuels to new renewable energy sources such as photovoltaic solar cells.

AUTHOR CONTRIBUTIONS

I. Idawati performed the literature analysis, experimental activities, writing of the manuscript, and analyzed the manuscript critically for significant intellectual content. N.A. Sasongko performed the literature analysis, data, and information collection, writing of the manuscript, and analyzed the manuscript critically for significant intellectual content. A.D. Santoso performed the data and information collection, data handling, validation, and LCA data analysis. W.S. Agam performed the experimental activities, data handling, validation, and LCA data analysis. H. Apriyanto performed the experimental activities, writing of the manuscript, and validation. A. Boceng performed the experimental activities, writing of the manuscript, and administration.

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CONFLICT OF INTEREST

The author declares no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
Al	Aluminium
ATP	Acidification terrestrial potential
CO_2	Carbon dioxide
CF	Carbon footprint
CFC	Chlorofluorocarbon
CH_4	Methane
DAP	Diammonium phosphate
Eq	Equivalent
Fe	Iron
FEP	Freshwater eutrophication potential
FEcP	Freshwater ecotoxicity potential
FRS	Fossil resources scarcity
GAP	Good agricultural practice
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
HCT	Human carcinogenic toxicity
HnCT	Human non-carcinogenic toxicity potential
IR	Ionizing radiation
ISO	International organization for standardization
KCl	Potassium chloride
kg	Kilogram
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LUP	Land use potential
Ltd	Limited
m^2	Square meter
m^2a *crop eq*	Square meter of change of land cover
MEcP	Marine ecotoxicity potential
MSA	mean species abundance

MEP	Marine eutrophication
MRS	Mineral resources scarcity
MSME	Micro, small and medium-sized enterprises
N_2O	Nitrous oxide
$(NH_4)_2HPO_4$	Diammonium phosphate granules
NPK	Nitrogen phosphate kalium
OC	Organic carbon
ODP	Ozone depletion potential
pH	Potential hydrogen
$PM_{2.5}$	Fine particulate matter
PPO	Plant pest organisms
PV	Photovoltaic
PMF	Particulate matter formation
PTCSR	Limited company chalodo sibali resoe
SFITAL	Sustainable farming in tropical Asian landscapes
TAP	Terrestrial acidification potential
TEP	Terrestrial ecotoxicity potential
USD	United States Dollar
UV	Ultraviolet
WS	Water scarcity

REFERENCES

Accatino, F.; Tonda, A.; Dross, C.; Léger, F.; Tichit, M., (2019). Trade-offs and synergies between livestock production and other ecosystem services. Agric. Syst., 168: 58-72 (**15 pages**).

Akrofi-Atitianti, F.; Ifejika Speranza, C.; Bockel, L.; Asare, R., (2018). Assessing climate smart agriculture and its determinants of practice in ghana: A case of the cocoa production system. Land. 7: 30 (**21 pages**).

Albaugh, T.J.; Albaugh, J.M.; Carter, D.R.; Cook, R.L.; Cohrs, C.W.; Rubilar, R.A.; Campoe, O.C., (2021). Duration of response to nitrogen and phosphorus applications in mid-rotation *pinus taeda*. For. Ecol. Manage., 498: 119578 (**15 pages**).

Alkemade, R.; Van Oorschot, M.; Miles, L.; Nellemann, C.; Bakkenes, M.; Ten Brink, B., (2009). Globio3: A framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems. 12: 374-390 (**16 pages**).

Amponsah-Doku, B.; Daymond, A.; Robinson, S.; Atuah, L.; Sizmura, T., (2022). Improving soil health and closing the yield gap of cocoa production in Ghana – A review. Sci. Afri. 15: e01075 (**11 pages**).

Armengot, L.; Beltrán, M.J.; Schneider, M.; Simón, X.; Pérez-Neira, D., (2021). Food-energy-water nexus of different cacao production systems from a LCA approach. J. Clean. Prod., 304: 126941 (**10 pages**).

Asitoakor, B.K.; Vaast, P.; Ræbild, A.; Ravn, H.P.; Eziah, V.Y.; Owusu, K.; Mensah, E.O.; Asare, R., (2022). Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana. Agric. Syst., 202:103476 (**9 pages**).

Ballesteros-Possú, W.; Valencia, J.C.; Navia-Estrada, J.F., (2022). Assessment of a cocoa-based agroforestry system in the southwest of colombia. Sustainability. 14: 9447 (**17 pages**).

Barišić, V.; Jozinović, A.; Flanjak, I.; Šubarić, D.; Babić, J.; Miličević, B.; Doko, K.; Ačkar, Đ., (2020). Difficulties with use of cocoa bean shell in food production and high voltage electrical discharge as a possible solution. Sustainability. 12.

Beg, M.S.; Ahmad, S.; Jan, K.; Bashir, K., (2017). Status, supply chain and processing of cocoa-a review. Trends Food Sci. Technol., 66: 108-116 (**9 pages**).

Bellard, C.; Bertelsmeier, C.; Leadley, P.; Thuiller, W.; Courchamp, F., (2012). Impacts of climate change on the future of biodiversity. Ecol. Lett., 15: 365-377 (**13 pages**).

Bianchi, F.; Moreschi, L.; Gallo, M.; Vesce, E.; Del Borghi, A., (2021). Environmental analysis along the supply chain of dark, milk and white chocolate: A life cycle comparison. Int. J. Life Cycle Assess., 26: 807-821 (**25 pages**).

Boakye-Yiadom, K.A.; Duca, D.; Pedretti, E.F.; Ilari, A. (2021). Environmental performance of chocolate produced in Ghana using life cycle assessment. Sustainability. 13:6155 (**20 pages**).

Büsser, S.; Jungbluth, N., (2009). LCA of chocolate packed in aluminium foil based packaging. Esu-services Ltd. Uster, Switzerland.

Caicedo-Vargas, C.; Pérez-Neira, D.; Abad-González, J.; Gallar, D., (2022). Assessment of the environmental impact and economic performance of cacao agroforestry systems in the ecuadorian amazon region: An LCA approach. Sci. Total Environ., 849: 157795 (**11 pages**)

Cheng, J.; Tiyaboonchai, A.; Yamashita, Y.M.; Hunt, A.J., (2011). Asymmetric division of cyst stem cells in drosophila testis is ensured by anaphase spindle repositioning. Development. 138: 831-837 (**7 pages**).

Dianawati, Nastiti, S.; Indrasti, Ismayana, A.; Yuliasi, I.; Djatna, T., (2023). Carbon footprint analysis of cocoa product Indonesia using life cycle assessment methods. J. Ecol. Eng., 24(7): 187–197 (**11 pages**).

Doe, E.K.; Attuaa, E.M.; Dogbatse, J.A.; Fosu-Mensah, B.Y., (2022). Assessing the condition and capability of soils in cocoa districts of Ghana using geovisualization. Soil Secur. 7: 100058 (**12 pages**).

Duan, B.; Man, X.; Cai, T.; Xiao, R.; Ge, Z., (2020). Increasing soil organic carbon and nitrogen stocks along with secondary forest succession in permafrost region of the daxing'an mountains, northeast china. Global Ecol. Conserv., 24: e01258 (**13 pages**).

Fardet, A.; Rock, E., (2020). Ultra-processed foods and food system sustainability: What are the links? Sustainability., 12: 6280 (**29 pages**).

Gaidajis, G.; Kakanis, I., (2020). Life cycle assessment of nitrate and inorganic fertilizers production—a case study. Sustainability. 13: 148 (**13 pages**).

Harya, G.I.; Budiwitjaksono, G.S.; Patiung, M., (2018). Competitiveness and processing of processed cocoa industry in improving the welfare of people's cocoa farmers in east java.

Nus. Sci. Technol. Proceed., 14 302-310 (**9 pages**).

Idawati; Hubeis; Fatchiya; Asngari, Tjitropranoto., (2018) The implication of climate adaptation and mitigation research: Capacity adaptation of rice paddy farmers to climate change. IOP Conference Series: Earth Environ. Sci., (**6 pages**).

Idawati, A.F.; Ariyanto, D., (2019). Sustainable cocoa farming strategies in overcoming the impact of climate change through sem pls 2. Int. J. Innov. Technol. Explor. Eng., 9: 291–297 (**7 pages**).

Idawati, I.; Sasongko, N.; Santoso, A.; Septiani, M.; Handayani, T.; Sakti, A.; Purnamasari, B., (2023). Cocoa farmers' characteristics on climate variability and its effects on climate change adaptation strategy. Global J. Environ. Sci. Manage., 10: 1-18 **(18 pages).**

Konstantas, A.; Jeswani, H.K.; Stamford, L.; Azapagic, A., (2018). Environmental impacts of chocolate production and consumption in the uk. Food Res. Int., 106: 1012-1025 (**20 pages**).

Misselbrook, T.; Van Der Weerden, T.; Pain, B.; Jarvis, S.; Chambers, B.; Smith, K.; Phillips, V.; Demmers, T., (2000). Ammonia emission factors for uk agriculture. Atmos. Environ., 34: 871-880 (**10 pages**).

Mugiyo, H.; Chimonyo, V.G.; Sibanda, M.; Kunz, R.; Masemola, C.R.; Modi, A.T.; Mabhaudhi, T., (2021). Evaluation of land suitability methods with reference to neglected and underutilised crop species: A scoping review. Land. 10: 125 (**24 pages**).

Muñoz, I.; Flury, K.; Jungbluth, N.; Rigarlsford, G.; Canals, L.M.; King, H., (2014). Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. Int, J Life Cycle Assess. 19: 109-119 (**11 pages**).

Nemecek, T.; Huguenin-Elie, O.; Dubois, D.; Gaillard, G.; Schaller, B.; Chervet, A., (2011). Life cycle assessment of swiss farming systems: Ii. Extensive and intensive production. Agric. Syst., 104: 233-245 (**13 pages**).

Ntiamoah, A.; Afrane, G., (2008). Environmental impacts of cocoa production and processing in ghana: Life cycle assessment approach. J. Clean. Prod., 16: 1735-1740 (**6 pages**).

Nuriana, W.; Anisa, N., (2014). Synthesis preliminary studies durian peel bio briquettes as an alternative fuels. Energy Procedia. 47: 295-302 (**8 pages**).

Ortiz-Rodríguez, O.O.; Villamizar-Gallardo, R.A.; Naranjo-Merino, C.A.; García-Caceres, R.G.; Castañeda-Galvís, M.T., (2016). Carbon footprint of the colombian cocoa production. Eng. Agric., 36: 260-270 (**11 pages**).

Parra-Paitan, C.; Verburg, P.H., (2022). Accounting for land use changes beyond the farm-level in sustainability assessments: The impact of cocoa production. Sci. Total Environ., 825: 154032 (**12 pages**).

Perez, M.; Lopez-Yerena, A.; Vallverdú-Queralt, A., (2021). Traceability, authenticity and sustainability of cocoa and chocolate products: A challenge for the chocolate industry. Crit. Rev. Food Sci. Nutr., 62: 475-489 (**15 pages**).

Permatasari, C.S.; Fahrizki, J.; Sasongko, N.A., (2019). Bioenergy power generation improved through biomass co-firing–a viewpoint of life cycle assessment (lca) method. Indones. J. Life Cycle Assess. Sustainability. 3(2): 33-40 (**8 pages**).

Rahmah, D.M.; Putra, A.S.; Ishizaki, R.; Noguchi, R.; Ahamed, T., (2022). A life cycle assessment of organic and chemical fertilizers for coffee production to evaluate sustainability toward the energy–environment–economic nexus in indonesia. Sustainability. 14: 3912 (**28 pages**).

Ramos, C.; Ruales, J.; Rivera-Parra, J.L.; Sakakibara, M.; Díaz, X., (2022). Sustainability of cocoa (*theobroma cacao*) cultivation in the mining district of ponce enríquez: A trace metal approach. Int. J. Environ. Res. Public Health. 19: 14369 (**12 pages**).

Ratnawati, B.; Yani, M.; Suprihatin, Suprihatin; Hardjomidjojo, H., (2023). Waste processing techniques at the landfill site using the material flow analysis method. Global J. Environ. Sci. Manage., 9(1): 73-86 (**14 pages**).

Recanati, F.; Marveggio, D.; Dotelli, G., (2018). From beans to bar: A life cycle assessment towards sustainable chocolate supply chain. Sci. Total Environ., 613: 1013-1023 (**11 pages**).

Rosmeika, R.; Hipia, M.A.; Sani, A.W.; Aditiyawana; Febriansyaha, H.; Andriyani, N.; Soraya, D.F.; Ayuningtyas, U.; Erliza, A.; Wardania, M.L.D.; Sari, C.K.; Septiani, M.; Pratiwi, A.I.; Sasongko, N.A.; Chairani, E., (2023). Environmental sustainability assessment of electric vehicle hybrid charging stations (HCS) for supporting the indonesian energy transition. SSRN. 4542751: 1-28 (**28 pages**).

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 (**7 pages**).

Santeramo, F.; Lamonaca, E., (2021). Food loss–food waste–food security: A new research agenda. Sustainability. 13: 4642 (**7 pages**).

Santoso, A.; Handayani, T.; Pinardi, D.; Kusrestuwardani, K.; Widyastuti, N.; Djarot, I.; Haryanti, J.; Sitomurni, A.; Apriyanto, H., (2023). Sustainability index analysis of microalgae cultivated in biorefinery palm oil mill effluent. Glob. J. Environ. Sci. Manage., 9: 559-576 (**17 pages**).

Sasongko, N.A.; Noguchi, R.; Ahamed, T., (2018). Environmental load assessment for an integrated design of microalgae system of palm oil mill in indonesia. Energy. 159: 1148-1160 (**18 pages**).

Sasongko, N.A.; Pertiwi, G.A., (2021). Life cycle cost (LCC) and the economic impact of the national biofuels development through biorefinery concept and circular economy. IOP Conf. Series: Earth Environ. Sci., 924:012074 (**7 pages**).

Sassen, M.; Soesbergen, A.V., (2022). Patterns of (future) environmental risks from cocoa expansion and intensification in West Africa call for context specific responses . Land Use Policy. 119: 106142 (**8 pages**).

Schreefel, L.; Schulte, R.; De Boer, I.; Schrijver, A.P.; Van Zanten, H., (2020). Regenerative agriculture–the soil is the base. Glob. Food Sec., 26: 100404 (**8 pages**).

Schroth, G.; Läderach, P.; Martinez-Valle, A.I.; Bunn, C.; Jassogne, L., (2016). Vulnerability to climate change of cocoa in west africa: Patterns, opportunities and limits to adaptation. Sci. Total Environ., 556: 231-241 (**11 pages**).

Sevilla, C.G., (2007). Research methods (quezon city: Rex printing company).

Sgroi, F., (2022). The circular economy for resilience of the agricultural landscape and promotion of the sustainable agriculture and food systems. J. Agric. Food Res., 8: 100307 (**5 pages**).

Singh, K.; Fuentes, I.; Fidelis, C.; Yinil, D.; Sanderson, T.; Snoeck, D.; Minasny, B.; Field, D.J., (2021). Cocoa suitability mapping using multi-criteria decision making: An agile step towards soil security. Soil Security. 5:100019 (**14 pages**).

Soulsbury, C.D.; Gray, H.E.; Smith, L.M.; Braithwaite, V.; Cotter, S.C.; Elwood, R.W.; Wilkinson, A.; Collins, L.M., (2020). The welfare and ethics of research involving wild animals: A primer. Methods Ecol Evol., 11: 1164–1181 **(18 pages).**

Suh, N.N.; Molua, E.L., (2022). Cocoa production under climate variability and farm management challenges: Some farmers' perspective. J. Agric. Food Res., 8: 100282 (**9 pages**).

Tothmihaly, A.; Ingram, V.; von Cramon-Taubadel, S., (2019). How can the environmental efficiency of indonesian cocoa farms be increased? Ecol. Econ., 158: 134-145 (**12 pages**).

Udawatta, R.P.; Jose, S., (2011). Carbon sequestration potential of agroforestry practices in temperate north america. Agrofor. Syst., 86: 225–242 (**18 pages**).

Walkiewicz, A.; Rafalska, A.; Bulak, P.; Bieganowski, A.; Osborne, B., (2021). How can litter modify the fluxes of co2 and ch4 from forest soils? A mini-review. Forests. 12: 1276 (**25 pages**).

Waluyo, J.; Haq, M.S.; Sari, A.A.; Putri, A.M.H.; Mastur, A.I.; Bardant, T.B.; Harianto, S.; Setiawan, A.A.R.; Sulaswatty, A.; Wiloso, E.I., (2018). Life cycle inventory of green tea production: Case of gambung. E3S Web Conference. 74: 1-6 (**6 pages**).

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Podcasts

CASE STUDY

Estimation of livestock greenhouse gas for impact mitigation

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ABSTRACT

BACKGROUND AND OBJECTIVES: Anthropogenic activities in livestock sectors are responsible for emitting substantial amounts of greenhouse gases, including carbon dioxide, methane, and dinitrous oxide, into the atmosphere, thereby contributing to climate change. The impact of these gases can be reduced through effective mitigation and adaptation efforts. This study aimed to estimate the livestock greenhouse gas emissions in Minahasa District, Indonesia; identify the greenhouse gas sources and distribution; and provide feasible mitigation options.

METHODS: This study used mixed methods to collect primary and secondary data from breeders and stakeholders in the Minahasa Regency. Interviews and questionnaires were also conducted, and the local government office provided secondary data. Breeders from various groups who lived in 25 different districts participated in this study, and the data analysis techniques used a Tier 1 model to process the data. The participants were included in focus group discussion activities for qualitative data collection to formulate potential mitigation strategies.

FINDINGS: The livestock sector emitted 48.83 gigagrams of carbon dioxide equivalent in 2021, and this was expected to increase by 24.98 percent in 2022, resulting in a total emission of 65.09 gigagrams of carbon dioxide equivalent. The sector also experienced a steady rise in emissions since 2010, with an average annual increase of 3.17 percent. The emissions were primarily composed of methane and dinitrous oxide, which accounted for 64.68 and 0.41 gigagrams carbon dioxide equivalent, respectively. In terms of livestock greenhouse gas distribution, the Sonder District produced 13.98 percent of the emission at 8.77 gigagrams of carbon dioxide equivalent. The main emissions resulted from methane manure management and enteric fermentation at 84.53 and 15.23 percent (7.41 and 1.34 gigagrams of carbon dioxide equivalent, respectively), while the remaining was composed of dinitrous oxide gas. In Kawangkoan District, the greenhouse gas emissions were dominated by methane from enteric fermentation and manure management, which accounted for 15.23 and 20.05 percent (5.63 and 1.43 gigagrams of carbon dioxide equivalent). In addition, the total emission accounted for 11.33 percent at 7.11 gigagrams of carbon dioxide equivalent.

CONCLUSION: The study produced an estimate of greenhouse gases from the livestock sector in the Minahasa Regency. During the studied period (2010-2022), the total greenhouse gas emissions exhibited an average annual increase of 3.17 percent. In 2022, the emissions consisted of methane and dinitrous oxide, with respective contributions of 99.38 percent per year and 0.62. Based on the spatial mapping, the Sonder District produced the largest cumulative emissions, primarily driven by emissions from animal waste management. Conversely, the Kawangkoan District dominated emissions stemming from the enteric fermentation of ruminant animals. These findings imply that all stakeholders in the Minahasa Regency should prioritize efforts to implement adaptation and mitigation programs to reduce these impacts.

NUMBER OF REFERENCES
54

NUMBER OF FIGURES
3

NUMBER OF TABLES
2

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INTRODUCTION

Climate change is widely acknowledged as one of the most urgent global issues. Numerous studies have documented the global commitment to diligently address and mitigate the diverse impacts stemming from ongoing climate irregularities, such as the evaluation of various methods for climate change adaptation and mitigation (Frimawaty *et al.*, 2023), investigation of hypothetical scenarios of climate variability (Abbas *et al.*, 2022), development of methods to minimize the negative impacts of climate change on food systems (Aryal *et al.*, 2020), and a review of studies on animal manure management for minimization of livestock CH_4 and N_2O emissions (Montes *et al.*, 2018). External and internal causes have triggered an uncertain climate, such as volcanic eruptions (Robock, 1990) and variations in solar radiation (Cohen *et al.*, 2020). Several consequences have been reported, including food insecurity (Mirzabaev *et al.*, 2022), water scarcity (Kushawaha *et al.*, 2020), drought (Konapala *et al.*, 2020), and various disasters, which disproportionately affect the world's most vulnerable populations (Chu *et al.*, 2017). Irregular temperatures and unpredictable rainy seasons have also increased food production costs due to chaotic supply chains (Godde *et al.*, 2021) and shortages of livestock products and food crops (Rahman *et al.*, 2022a) combined with damage caused by landslides and floods (Winter *et al.*, 2019). Ecological changes have decreased livestock (Cheng *et al.*, 2021) and agricultural production (Rahman *et al.*, 2022a), including behavioral changes in various animal species and reductions in biodiversity (Rahman *et al.*, 2022b). Greenhouse gases (GHGs) are gases that cause the greenhouse effect in the earth's atmosphere. GHGs can trap heat within the Earth's atmosphere, and the mechanism of action is related to capturing heat (Forsters *et al.*, 2007). According to the United Nations Environment Program (UNEP, 1989), there are six types of gases classified as GHGs, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbon (PFC), and sulfur hexafluoride (SF_6). These gases include CO_2, CH_4, and N_2O, as well as synthetic chemicals such as fluorine (F) (Anderson *et al.*, 2016). Under normal conditions, this greenhouse effect serves to keep the Earth's temperature warm to sustain life (Kweku *et al.*, 2018). However, the amount and concentration of GHGs have risen significantly, impacting the severity of global warming (Ding *et al.*, 2017). CH_4 has a concentration of 1,745 parts per billion (ppb) or approximately 0.000175 percent (%) (Forsters *et al.*, 2007). The concentrations rise by 1% annually and contribute to 15-20% of the total GHG effect (Forsters et al., 2007). The global average temperature has increased by approximately 1 degree of Celsius (°C) since the pre-industrial era and CO_2 concentrations in the global atmosphere are currently over 408 ppm, while N_2O and CH_4 are at 331.1 ppb and 1858 ppb (Tang *et al.*, 2022). According to recent studies, global warming caused storm surges and winds that vary greatly, including cyclone activity (Camello *et al.*, 2022) and higher sea levels (Vousdoukas *et al.*, 2018). The environment, economy, and health sectors have experienced many impacts (Rocha *et al.*, 2022). The degradation of air quality resulting from forest fires and the combustion of fossil fuels have had wide-ranging adverse impacts on human health (Purohit *et al.*, 2023). Greenhouse gas emissions affect public health and the economy through a number of mechanisms related to climate change and environmental pollution. Emissions of greenhouse gases such as CO_2, CH_4, and N_2O can result in more frequent and extreme heat waves, potentially threatening public health with risks of heat exhaustion, dehydration, and even death (Gavuvora *et al.*, 2021). In specific regions, the onset of several diseases has become apparent due to exposure to heat waves (Arsad *et al.*, 2022), such as respiratory, cardiovascular, and waterborne diseases (Liu *et al.*, 2022), along with concerns related to malnutrition (Fanzo *et al.*, 2021 and Dietz, 2019). GHG emissions are often linked to burning fossil fuels, which also produce air pollutants such as fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_x) that can trigger or worsen respiratory health problems such as asthma, bronchitis, and chronic obstructive pulmonary disease (Eckelman *et al.*, 2016). Climate change can also affect patterns of disease spread as warmer and humid climates can expand the area of distribution of disease vectors such as mosquitoes, which can increase the risk of diseases such as malaria, dengue, and Zika. Greenhouse gas emissions contribute to the effects of climate change, such as more frequent and prolonged droughts (Manisalidis *et al.*, 2020), which can disrupt agriculture and cause food shortages, malnutrition, and hunger in various regions, which in turn, can have a negative impact on public health

(Rocha, *et al.,* 2022). Greenhouse gas emissions also have an impact on the economy. Global GHG emissions have had long-term effects on sub-Saharan Africa's economic growth. In general, there will be a concomitant decline between economic growth and environmental quality in the long term, but if CO2 emission levels are significantly reduced in the future, there could be an increase in GDP. For such observations to be realized, the role of technology becomes very important (Adzawla *et al.,* 2019). Another study showed that the impact of GHG emissions on economic factors for China and the United States is different. China's economic factors are known to increase greenhouse gas emissions, while in America, it is precisely the opposite and there is a reduction in greenhouse gas emissions. However, we found strong evidence that renewable energy production leads to sustainable development in the US and China (Yamaka *et al.,* 2021). Human activities constantly affect the atmospheric composition, such as increased concentrations of GHGs (Chataut *et al.,* 2023). The rise in the CO_2 concentration is attributed to the burning of fossil fuels for electricity, heat, and transportation (Bradbury *et al.,* 2015), microbial decomposition processes (Yasmin *et al.,* 2022), and unchecked land conversion (Malik *et al.,* 2023). The livestock sector emits two leading gases: CH_4 and N_2O. Enteric fermentation of ruminants and manure manufacturing, including storage, produce CH_4 emissions (San Martin Ruiz *et al.,* 2022) that can cause global warming 28 times greater than CO_2, while N_2O, which is mainly generated from the processing of animal waste, has the potential to be 265 times stronger than CO_2 (Grossi *et al.,* 2019).

Methane is a greenhouse gas commonly produced in the context of animal husbandry by the digestive process of ruminant animals, such as cows, sheep, and goats. In their digestive system, fermentation occurs which produces methane as a byproduct (Min *et al*., 2022). The methane is then excreted through the eructation and flatulence of these animals. The methane gas released from the digestion of these animals is called enteric methane. Aside from the digestive system of ruminants, methane can also be produced from livestock waste fermented in manure and sludge (Orzuna-Orzuna *et al*., 2021). This occurs in animal manure storage areas, such as manure barns or mud tanks, where anaerobic conditions

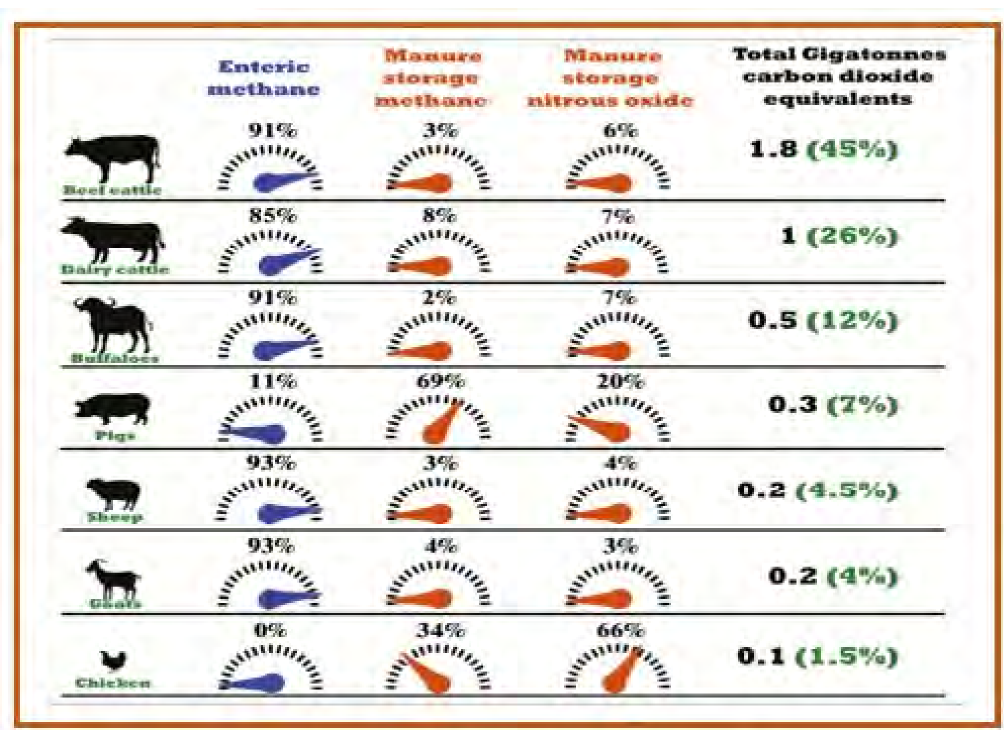

Fig. 1: GHG incidence of enteric fermentation and manure storage by animal type (Gt/CO_2-eq) (Grossi, 2019)

(without oxygen) result in methane production. Nitric oxides (N_2O) are greenhouse gases that can also be produced by livestock. One of the main sources of N_2O is synthetic fertilizers, especially nitrate fertilizers, which are used to promote the growth of animal feed crops. In addition, nitrogen oxides can also be produced from the process of nitrogen decomposition in soil and animal waste (denitrification), especially when there is an excess of nitrogen nutrients in agricultural or livestock systems (Yasmin *et al*., 2022). The demand for livestock products is mainly triggered by increasing population growth, urbanization, and rising incomes, especially in developing countries (UN, 2017). The growing global population leads to a substantial increase in the demand for livestock meat. Projections indicate that market demand for chicken meat, eggs, and pork is expected to increase by 32%, 61%, and 39% from 2005 to 2030 (Gerber *et al.,* 2013). Still, according to Gerber, the livestock sector absorbs enough natural resources so that this sector contributes around 14.5% of the total anthropogenic GHG emissions or 7.1 gigatons carbon dioxide equivalent per year (Gt/CO_2-eq/y) in 2005 (Gerber *et al.,* 2013). In Indonesia, animal husbandry is a crucial sector, particularly for rural communities who depend on it for their livelihoods. The sector employs around 3.84 million workers, 3.17% of Indonesia's total workforce (BPS. 2021). Based on a report from the Ministry of the Environment's Directorate General for Climate Change, in 2020, the total GHG emission from the three primary gases (CO_2, CH_4, and N_2O) was 1,050,413 gigagrams carbon dioxide equivalent per year (Gg/CO_2-eq), with the livestock sector contributing 33,182 Gg/CO_2-eq (MEFRI, 2022). This is due to the increase in the population of several types of livestock, especially poultry, which has experienced a significant increase in population. Minahasa is one of the regencies in the Indonesian region. It has an area of 121,043.31 hectare (ha), consisting of 25 districts. The leading commodity is swine farming, with a population of 174,697 heads, followed by beef cattle, with 34,267 heads (BPS, 2023). With the potential of this region, there is a need for livestock GHG estimation. However, there is a lack of regional GHG inventories. This is reinforced by the absence of an integrated mitigation program for the livestock sector of the Minahasa Regency. Some breeders carry out incidental mitigation activities, but many do not. The existence of the Presidential Regulation of the Republic of Indonesia No. 61 of 2011 requires every regency in all regions of Indonesia to create a Regional Action Plan for GHG Mitigation, and the insufficient knowledge of breeders about greenhouse gases and their mitigation also highlights the need for this study. Many country-level GHG emission studies have been conducted, but few at the regional level. Hence, the availability of academic information on GHG emissions is minimal. This study was conducted to fill this gap by estimating livestock GHGs based on data on livestock population potential and emission factors. The uniqueness of this study is that its implementation is not only carried out by the research team but also involves farmers and local governments, from data collection to potential mitigation formulations, to increase awareness and knowledge of all parties to ultimately reduce the ongoing impact of climate change and minimize disparities in data accuracy. Thus, this study aims to estimate livestock GHG emission in the Minahasa Regency, map the GHG emission burden distribution for each district area, and provide a feasible GHG mitigation program. This study was conducted in the Minahasa Regency, North Sulawesi Province, Indonesia, in 2023 (Fig. 2).

MATERIALS AND METHODS

The study used a mixed method design, which combined quantitative and qualitative approaches in the form of analytical descriptive studies. In this study, the Tier 1 model was used as an estimation model. The Tier 1 models defined by the IPCC (Intergovernmental Panel on Climate Change) (Dong *et al.,* 2006) have varying degrees of complexity ranging from Tier 1 models based on default global or regional emission/removal factors, Tier 2 models based on local emission/removals factor; and Tier 3 models which involve more detailed modeling or inventory-based approaches. In this study, the Tier 1 model was used due to several reasons including limited activity data based on the type, age class, and local emission factor of each type of livestock and unavailability of livestock GHG inventory data (Dong *et al.,* 2006; IPCC, 2006). The Tier 1 model has a fundamental equation that multiplies information regarding human activities over a specific period (referred to as activity data, AD) with emissions factors associated with those activities (emission/absorption factors, EF). This equation is expressed as GHG

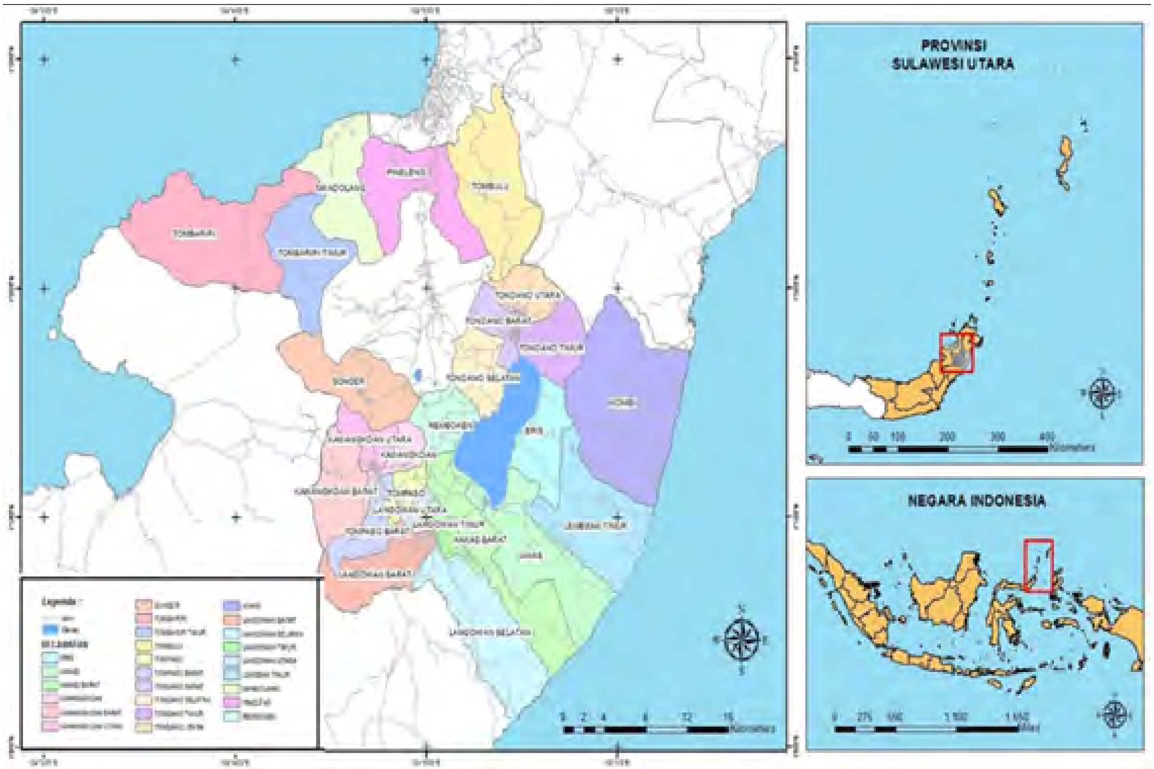

Fig. 2: Geographical location of the study area in Minahasa Regency, Indonesia. The study was conducted in 25 district locations, identified by various colors (except White color)

emissions = AD x EF, where AD is the activity data and EF denotes the emission factor. The Global Warming Potential (GWP) value was used to convert non-CO_2 GHG emission data into carbon dioxide equivalent (CO_2-eq) (CH_4= 21 and N_2O= 310). To estimate livestock GHG emissions, many activity datasets will be used, as well as the assumption that GHG emissions from the livestock sector primarily arise from two sources: 1) CH_4 from enteric fermentation of ruminant (cattle beef and goats) and non-ruminant animals (swine and horse) and poultry; and 2) the emissions of N_2O that occur during the storage, processing, and natural decomposition of solid and liquid livestock manure. The study included respondents representing breeder groups who carried out their respective activities across 25 districts in the Minahasa Regency. The included breeders were those with the most livestock ownership (the top five). The livestock data included cattle, horse, swine, and poultry counts, amount of manure excreted per head of animal type, and manure management system. Secondary information, such as animal population, was obtained from the BPS Minahasa Regency and the Office of Minahasa Regency Agriculture and Livestock. The data on the emission factors were derived from the 2006 IPCC documents. Arcmap was chosen as a geographic information system (GIS)-based application that can process, select, and display data about locations. This analysis involved determining the scale, accuracy of attributes, accuracy of data, and data structure and determining the distribution of GHG emissions in each district in the Minahasa Regency. The results are presented as a map of the distribution of GHG emissions based on all study areas of the 25 districts for the livestock sectors. In this study, breeders and the local government were involved in focus group discussion (FGD) activities to produce qualitative data and to verify the secondary data that was obtained. In this case, the breeder is not a passive participant but an expert on manure management, feeding, and other activities. This is what distinguishes this study from other case studies. The CH_4 emissions from

Table 1: Emission factor of animal type

Animal type	Enteric fermentation	Manure management
Cattle beef	47	0.02
Goat	5	0.02
Horse	18	2.19
Swine	1	7
Poultry	-	0.02

enteric fermentation were determined by multiplying activity data (e.g., population size) by an emission factor, using Eq. 1 (Dong *et al.,* 2006).

$$\text{Emission of } CH4 = EF_{(T)} \times N_{(T)} \times 10^{-6}{}_{\text{Enteric Fermentation}} \quad (1)$$

Where; CH_4 emissions = enteric fermentation CH_4 emissions ($Gg/CH_4/y$)

$EF_{(T)}$ = enteric fermentation emission factor of each animal type ($kg/CH_4/head/y$)

$N_{(T)}$ = number of animals per type.

Both primary kinds of animals are assumed to be animal units and calculated using Eq. 2 (MEFRI, 2019).

$$N_{(T)}\text{in Animal Unit} = N_{(x)} \times K_{(T)} \quad (2)$$

Where;

$N_{(T)}$ = Total animal unit;

$N_{(X)}$ = number of farm animals (heads)

$K_{(T)}$ = correction factor: cattle 0.75

T = types of animal

The CH_4 emissions from managed manure: estimated using Eq. 3 (Dong *et al.,* 2006).

$$\text{Emission of } CH4_{\text{ Manure Managed}} = \sum_T EF_T . N_{(T)} . 10^{-6} \quad (3)$$

Where:

$CH_{4\,Manure}$ = CH_4 emissions from manure management ($Gg/CH_4/y$)

$EF_{(T)}$ = emission factor, $kg/CH_4/head/y$

$N_{(T)}$ = number of animal species

T = animal species.

The N_2O Emissions from manure management were estimated using Eq. 4 (Dong *et al.,* 2006).

$$EmissionN_2O_{D(mm)} = \left[\sum_S \left[\sum_T \left(N_{(T)} . Nex_{(T)} . MS_{(T,S)} \right) \right] . EF_{3(S)} \right] . \frac{44}{28} \quad (4)$$

Where:

Emission $N_2O_{(mm)}$ = direct N_2O from manure management, $kg/N_2O/y$

$N_{(T)}$ = animal category *T*

$Nex_{(T)}$ = N animal excretion average (kg/N/animal/y), which was estimated using Eq. 5 (Dong *et al.,* 2006).

$$NEX_{(T)} = N_{(T)} \times \frac{TAM}{1000} \times 365 \quad (5)$$

Where:

TAM = standard weight of animal for each animal type T (kg/head);

$MS_{(T,S)}$ = fraction of N excretions managed (cattle=0.2, goat=0.1, swine=0.3, horse=0.07, poultry=0.3)

$EF_{3(S)}$ = emission factor (kg/N_2O-N/kg/N)

S = manure management system

T = Animal species

44/28 = conversion of $(N_2O\text{-}N)_{(mm)}$ to $N_2O_{(mm)}$

N losses due to volatilization from manure management were estimated using Eq. 6 (Dong *et al.,* 2006).

$$N_{volatilization-MMS} = \sum_S \left[\sum_T \left[\left(N_T . Nex_{(T)} . MS_{(t,S)} \right) . \left(\frac{Frac_{GasMS}}{100} \right)_{(T,S)} \right] \right] \quad (6)$$

where:

$N_{volatilization-MMS}$ = nitrogen lost due to volatilization of NH_3 and NO_x (kg/N/y)

$N_{(T)}$ = animal number

$Nex_{(T)}$ = annual average N excretion (using Eq. 4)

$M.S._{(T,S)}$ = fraction N excretions managed (cattle=0.2, goat=0.1, swine=0.3, horse=0.07, poultry=0.3)

$Frac_{GasMS}$ = percent of managed manure N that volatilizes as NH_3 and NO_x (cattle 30%, swine 25%, poultry 40%, and other 30%)

The indirect N_2O emissions from volatilization of N in the forms of NH_3 and NO_x ($N_2OG_{(mm)}$) were estimated using Eq. 7 (Dong *et al.,* 2006).

$$N_2O_{G(mm)} = \left[N_{volatisation-MMS} . EF_4 \right] . \frac{44}{28} \quad (7)$$

where:

$N_2O_{G(mm)}$ = indirect N_2O emissions (volatilization of N manure management), kg/N_2O/y

EF_4 = emission factor for N_2O emissions from atmospheric nitrogen deposition on soils and water surfaces; the default value is 0.01 kg/N_2O/N (kg/NH_3-N + NO_x-N/volatilized), which was estimated using Eq. 8 (Dong *et al.,* 2006).

The value of 44/28 is conversion of of $N_2O\text{-}N_{(mm)}$ to $N_2O_{(mm)}$ (8)

RESULTS AND DISCUSSION

To estimate GHG emission in the livestock sector requires data on emission factors (Table 1) and activity data in the form of livestock population data (Table 2).

Based on the estimations, the livestock sector in the Minahasa Regency in 2022 produced a total GHG emission of 65.09 Gg/CO_2-eq/y and this emission has increased by 24.98% compared to the total emission in 2021, amounting to 48.83 Gg/CO_2-eq/y. Compared with the emission in 2010 of 41.45 Gg/CO_2-eq/y, this increased by 36.31% or to 65.09 Gg/CO_2-eq in 2022. During the studied period (2010-2022), greenhouse gas emissions in the Minahasa Regency experienced a threefold increase (Fig. 3). Specifically, the periods 2011-2013 and 2016-2020 exhibited an average

Table 2: Animal population in Minahasa Regency (head)

Year	Cattle	Goat	Horse	Swine	Poultry
2010	24,709	3,025	6,054	96,725	1,231,309
2011	25,730	3,026	6,054	96,727	1,231,308
2012	28,036	3,023	5,902	108,363	1,382,515
2013	27,291	3,202	6,710	123,401	1,928,999
2014	20,559	2,682	4,379	113,757	2,226,633
2015	23,499	2,601	3,984	117,896	2,253,670
2016	19,999	2,239	4,107	124,087	1,413,596
2017	27,034	1,819	3,150	136,157	2,892,925
2018	28,400	2,127	3,201	127,400	3,099,475
2019	25,906	2,007	3,650	129,944	3,168,191
2020	24,972	2,007	3,568	128,721	3,150,330
2021	26,761	1,987	3,024	130,969	3,193,893
2022	34,267	2,143	3,025	174,697	3,541,523

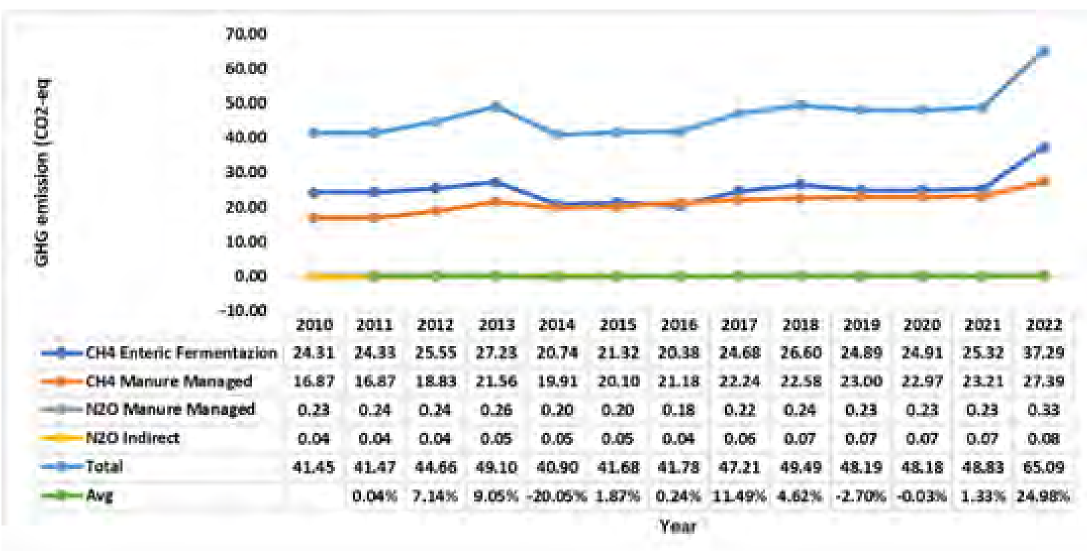

Fig. 3: Graphic of livestock GHG inventory describes fluctuations in total GHG emissions per year (2010-2022). The highest increase occurred in the period 2021-2022

increase of 8.09% and 18.11%, while the 2021-2022 period witnessed a substantial increase of 24.98%. The total greenhouse gas emissions from the livestock sector in the Minahasa Regency exhibited an average annual increase of 3.17% (Fig. 3).

This is in line with the characteristics of the Minahasa Regency area as a center for supplying livestock products for the province of North Sulawesi. The increase in GHG emissions was mostly due to the increase in the population of the two main types of livestock, namely swine and cattle, which increased, on average, by 4.39% and 1.48% per year. The marked increase in last two years (2021-2022) was attributed to the high population of animals driven by the rising demand for livestock meat due to the prevalent trend of hosting parties and celebrations in the Minahasa Regency. In 2021-2022, following the government's declaration that the COVID-19 pandemic was over, there were euphoric sentiments, including increased party activities. In Minahasan society, a party culture represents a pervasive form of social activity that is seamlessly integrated into daily life, including events such as birthday celebrations, wedding anniversaries, thanksgiving gatherings, and various other occasions. This cultural phenomenon resulted in a substantial impact on the escalating demand for livestock products. The analysis of livestock population data showed a 21.90% and 25.03% increase in the number of cattle and swine in 2021-2022. These two categories of animals are extensively consumed during these festivities, and are used to meet the daily dietary requirements of the local community. GHG emissions from livestock were primarily attributed to increased enteric fermentation of CH_4 when categorized by gas type. According to estimation data for the year 2022, the most substantial source was the total CH_4 emissions, amounting to 64.68 Gg CO_2-eq/y, followed by total N_2O emissions of 0.41 Gg CO_2-eq/y. The contribution of each gas is shown in Fig. 4.

The main source of methane gas (CH_4) emissions is the digestive process of farm animals, especially in ruminants such as cows, buffaloes, goats, and sheep. Ruminants have specialized digestive systems that involve microbial fermentation in their stomachs to break down fiber—vegetables, grass, hay, and other forages—which produce methane as a byproduct of this digestive process. The methane produced in the digestive tract of these ruminant is called enteric fermentation methane (Orzuna-Orzuna *et al.*, 2021). The increase in gas production is highly dependent on the type and quality of feed consumed (Min *et al.*, 2022). High-fiber, low-energy digestible feed types resulted in higher CH_4 emissions due to increased microbes for fermentation (Guo *et al.*, 2022). Non-ruminant animals also produce CH_4, but at much lower levels than ruminants (Chang *et al.*, 2019). The microbial populations and activity of non-ruminant animals differ from those of ruminants, leading to lower methane production (Montes *et al.*, 2018). Apart from the digestion of ruminants, livestock manure management can also contribute to methane gas emissions. Animal manure, such as feces and urine, contain ingredients that can produce methane if not managed properly, especially in anaerobic conditions (without oxygen). Managing this manure through composting can also result in

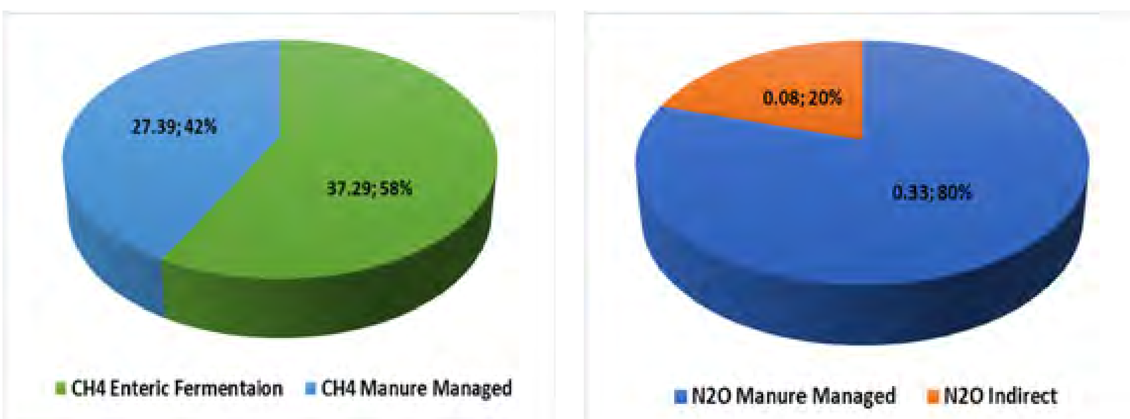

Fig. 4: Contribution of CH_4 and N_2O to total livestock GHG's

an increase in CH_4 emissions, with a simultaneous reduction in N_2O emissions, directly and indirectly, by 0.47% and 0.14%. Manure could be blended with other materials, such as straw or dry leaves, to foster aerobic conditions. This approach promotes the proliferation of aerobic microorganisms that facilitate the decomposition of organic matter and mitigate N_2O production (Yasmin *et al*., 2022). Therefore, methane emission reductions in the livestock sector are often focused on efforts that optimize animal feed nutrition and management, as well as animal waste management to reduce the impact of waste digestion and decomposition on methane production. Based on spatial analysis, the total distribution of GHG emissions from the livestock sector across the 25 districts in the Minahasa Regency is depicted in Fig. 5. The highest emissions were observed in the Sonder District, accounting for 13.98% (8.77 Gg/CO_2-eq) of the total emissions. Furthermore, the primary contributors were CH_4 from manure management and enteric fermentation, accounting for 84.53% (7.41 Gg/CO_2-eq) and 15.23% (1.34 Gg/CO_2-eq), and the remainder was attributed to N_2O gas. In the Kawangkoan District, GHG emissions were primarily driven by CH_4 enteric fermentation, accounting for 15.23% (5.63 Gg/CO_2-eq), and CH_4 emissions from manure management, contributing 1.43 Gg/CO_2-eq (20.05%). The total emission from the Kawangkoan District amounted to 7.11 Gg/CO_2-eq (11.33%).

These findings are consistent with several studies reporting that 14.9% of China's total GHG emissions come from the enteric fermentation of beef cattle, which produces CH_4 emissions (Guo *et al.,* 2022). In the Andean region, Southwest Colombia, the highest emissions are produced from CH_4 due to enteric fermentation (2,963 kg CO_2-eq/ha/y; 38% of total emissions) (Parra *et al.,* 2019). Approximately 70% of Australia's total agricultural emissions come from methane emissions from sheep, goats, horses, pigs, and cattle (Panchasara *et al.,* 2021). Farm animals generate a substantial amount of manure, with varying degrees of management practices in place. In Indonesia, a significant number of breeders continue to permit their livestock to graze freely within coconut plantations. Consequently, the fecal waste remains either deposited on the ground or inadequately managed. This result is in line with studies conducted by Frimawaty *et al*., (2023) where

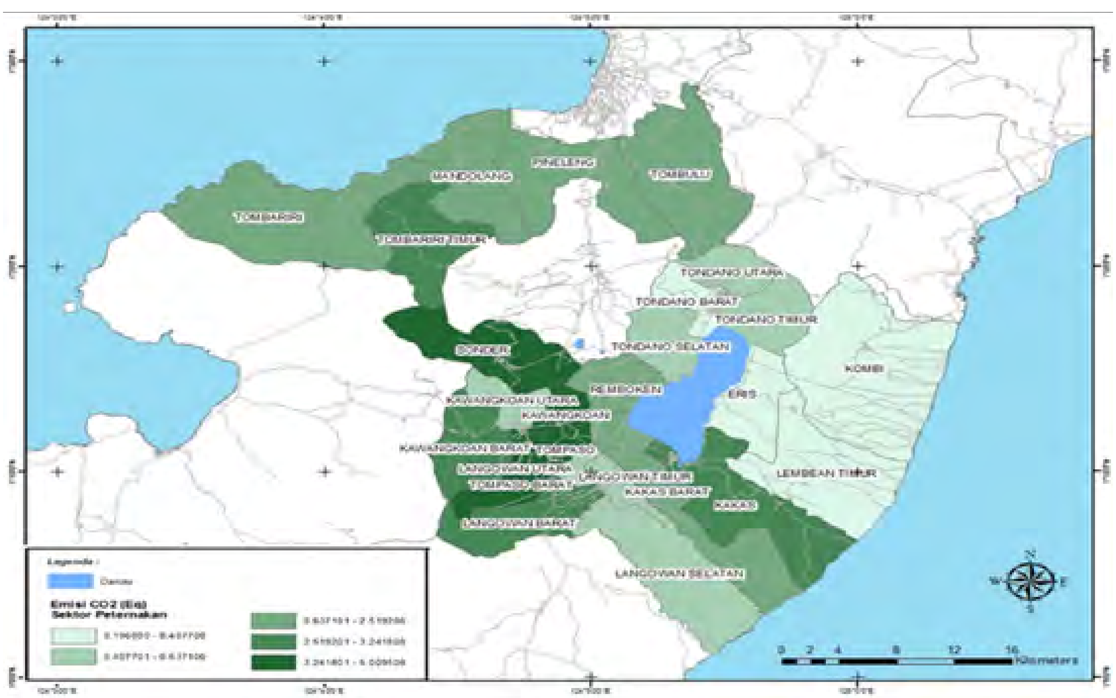

Fig. 5: Map of distribution of CH_4 gas emitted by the Livestock sector. Dark green indicates the largest CH_4 emissions spread, and pale green indicates the smallest emission

14.3% of the breeders in South Sulawesi Province, Indonesia, have already managed cattle manure in the farming. Meanwhile, 85.7% have not applied the management practices and 63.2% of manure is still left and piled up in open spaces. The GHG emissions produced will be greater than those of well-managed animal waste. As a result, these GHG emissions will produce a series of complex reactions involving the atmosphere, solar radiation, and energy flow patterns on Earth. Excessive GHG emissions will accumulate in the atmosphere, where the accumulation will form a kind of ”blanket” which can capture the infrared radiation reflected by the Earth. This goes on continuously and over a long period of time, causing an increase in the average temperature of the Earth’s surface, known as global warming. This increase in global temperatures has an impact on the environment and climate system, including changes in rainfall patterns, rising sea levels, increasing frequency and intensity of extreme weather events such as storms and droughts, and more extreme seasonal changes. Rising temperatures can also affect the Earth’s water cycle, such as melting polar ice caps, changes in rainfall patterns, and other impacts on the hydrological cycle, threatening the availability of clean water, the sustainability of aquatic ecosystems, and the agricultural sector. Climate change can also affect ecosystems, including shifts in geographic boundaries for some species, changes in animal migration and behavior, and biodiversity loss. These mechanisms work in tandem and influence each other, resulting in observable climate change such as global warming and its diverse impacts. The effects of climate change can vary widely across regions, and can have long-term impacts on ecosystems, both socially and economically. GHG emission mitigation and adaptation to climate change are very important to maintain the sustainability of the environment and human life in the future. In predicting the GHG emissions of these farms, researchers face obstacles in obtaining data because not all data is available. This difficulty is overcome by collecting historical data on livestock operations, such as feed consumption and waste management to help in understanding trends and patterns that can help to estimate GHG emissions. This data can only be obtained by actively involving farmers and local governments, either in FGD forums or other informal forums. By using this strategy, the verification of data at the source of origin can also be conducted directly because the data collected has been verified since the beginning. The adaptation and mitigation strategies discussed have been formulated through analysis, discussions, and interviews with breeders representing their respective groups. These strategies are also consistent with previous studies deemed suitable for implementation. The breeders’ participation in the FGD was aimed at developing an effective GHG mitigation plan. Various adaptation and mitigation initiatives researched and developed by the Ministry of Agriculture of Indonesia can be utilized as inputs for their implementation. Few of the results can be implemented in the Minahasa Regency for various reasons, including incompatibility with local conditions, unavailability of evidence of the effectiveness of these measures, and lack of technical understanding regarding the standards offered. Breeders have also contemplated various potential efforts and actions for implementation. The need for practical knowledge has been implemented concerning greenhouse gases, particularly those affecting the livestock sector. Several initiatives to be conducted include extensive outreach on greenhouse gases and climate change through social media, mainstream media, or community meetings. This study is perceived as a valuable addition, specifically in enhancing the understanding and knowledge of greenhouse gases and climate change. Several conditions are still needed for the feasibility for the application of this mitigation program, such as lab tests (for tannin and seaweed use programs) and political coordination with the government for biogas programs. There are some mitigation measures that can be presented to breeders for implementation:

1) Using tannins in feed by mixing local feed ingredients with tannin compounds. This method has proven highly effective in significantly reducing methane gas emissions, as tannins can mitigate methane production during digestion and inhibit the growth of methanogenic bacteria (Jayanegara *et al.,* 2009). Breeders have expressed the need for additional empirical evidence to substantiate these claims. Researcher team promised breeders that after conducted trials first in the laboratory, the results will be presented. After that stage, field trials will be carried out involving several samples. If the results are significant, it will be applied to all livestock through the Minahasa Regency Agriculture Office.

2) Supplying forage to livestock is essential and

the agricultural sector should not be overlooked as a contributor to methane gas production. The Agricultural Research and Development Agency of the Ministry of Agriculture has introduced green leaves, which have relatively low levels of methane gas emissions, as an alternative source of animal feed. These leaves are sourced from Leguminosa, Gliricida leucaena, and Calliandra plants known for their tannin and saponin content. Breeders can consider this approach as a viable response. Some have and are applying this type of feed to their livestock by concocting their own types of kaliandra leaves into additional feed. However, the results still need further research to obtain empirical evidence so that it is implemented by all breeders. It is also necessary to involve the Minahasa Regency Agriculture Office to carry out technical facilitation.

3) Providing animal feed with seaweed is a recent development in livestock management. Recent studies have shown that incorporating seaweed into cow feed can result in an impressive 86% reduction in methane emissions. Specifically, the supplementation of dairy cow feed with 0.25% to 0.50% Asparagopsis taxiformis, a red seaweed, has been reported to achieve substantial reductions in methane gas production. This reduction in methane emissions can range from 50% to 74% over a period of 147 days. The inclusion of red seaweed (Asparagopsis taxiformis) in the diet can reduce enteric methane gas emissions by over 80% (Roque *et al.,* 2021). Breeders may require concrete evidence of its effectiveness before implementing this approach. This also still requires further research, considering that, in this area, it is quite difficult to obtain seaweed raw materials.

4) The implementation of biogas production on farms is a viable approach for harnessing CH_4 gas, a byproduct of agriculture and livestock activities, by using microorganisms to convert agricultural and livestock waste into biogas. Biogas offers numerous benefits and advantages: a) it can serve as an alternative energy source, effectively substituting fossil fuels; b) function as a renewable energy source, ensuring long-term sustainability; c) contribute to pollution reduction through the processing of organic waste; d) provide support to the local economy by creating opportunities for economic growth; e) yield valuable solid and liquid organic fertilizers; and f) enhance environmental sanitation and hygiene standards. Breeders can initiate this approach with financial support from the local government. Building biogas reactors is not too difficult and in some regions it has been achieved. In the Minahasa Regency, it could be implemented but it must involve the local government, especially in financing the manufacture of reactors.

CONCLUSION

In conclusion, the livestock sector in the Minahasa Regency was reported to contribute to GHG emissions primarily in the form of CH_4 and N_2O gases. In 2010, this sector emitted 48.83 Gg/CO_2-eq of GHG emissions, which increased by 24.98% to 65.09 Gg/CO_2-eq in 2022. This marked a significant rise compared to the emission of 41.45 Gg/CO_2-eq/y in 2010, experiencing a substantial increase of 36.31% by 2022. In the studied period, GHG emissions experienced three distinct periods of increase in 2011-2013, 2016-2018, and 2021-2022 with an average increase of 8.09%, 18.11%, and 24.98%. The cause was attributed to the growth of the animal population, driven by the demand for livestock meat. This demand was a direct consequence of numerous social activities, such as parties and celebrations, which are deeply embedded in the culture of the Minahasa tribe. The 2021-2022 period coincided with the government's declaration of the end of the emergency status in response to the COVID-19 pandemic. This declaration was met with enthusiasm by the public, leading to an increase in the hosting of various parties. This phenomenon was underscored by a substantial increase in the cattle and swine populations by 21.90% and 25.03% during the 2021-2022 period. Based on the type of gas emitted, the livestock sector primarily released CH_4 and N_2O. The predominant source was CH_4 emissions, amounting to 64.68 Gg/CO_2-eq, followed by N_2O emissions at 0.41 Gg/CO_2-eq. The substantial methane gas emissions were also primarily attributed to the sizable population of ruminant animals, such as cows and goats. These animals produced more methane gas due to the digestive process. In contrast, non-ruminant animals also emitted methane, but the emissions were considerably lower. Concerning the distribution of livestock greenhouse gas emissions, the Sonder District accounted for emissions of 8.77 Gg/CO_2-eq (13.98%), where the most significant contributor was CH_4 from manure management and enteric fermentation, amounting to 7.41 Gg/CO_2-

eq (84.53%) and 1.34 Gg/CO_2-eq (15.23%), and the remainder was attributed to N_2O gas. In contrast to the Sonder District, in the Kawangkoan District, GHG emissions were primarily dominated by CH_4 from enteric fermentation and manure management, amounting to 5.63 Gg/CO_2-eq (15.23%) and 1.43 Gg/CO_2-eq (20.05%), with a total emission of 7.11 Gg/CO_2-eq (11.33%). The knowledge derived from these findings implies that climate change and its various phenomena were a reality, necessitating concrete actions for mitigation and adaptation. These actions could be undertaken collaboratively at the global, regional, and national levels. Breeders, in collaboration with the government and other stakeholders, also implemented various adaptation and mitigation measures. These measures included conducting a climate change assessment to minimize its adverse impact on the livestock sector, undertaking a range of actions to adapt natural and social systems to cope with the effects of climate change, and making efforts to reduce emissions sources while enhancing greenhouse gas absorbers. The efforts were accomplished through various mitigation strategies, such as mixing local feed ingredients with tannin compounds, providing forage to livestock, supplementing animal feed with seaweed, and implementing biogas production on farms. The role of the Minahasa Regency Agriculture Office is necessary, especially in facilitating both technical and non-technical aspects, such as program financing. The results of this study are expected to benefit other researchers, especially for climate change science and GHG estimation so that more and more varied GHG mitigation approaches can be developed according to the characteristics of the region and source. For breeders, it is expected to increase awareness to carry out various GHG mitigation efforts to reduce the impact of climate change. In this study, there are several limitations such as not using statistical analyses, estimates of GHGs were only based on emissions from animals, and there was no discussion of the socioeconomic feasibility of the mitigation programs. These limitations are directions for future studies including by other researchers.

AUTHOR CONTRIBUTIONS

D.S.I. Sondakh, as the first and corresponding author, has contributed to preparing, writing, and finishing the manuscript, F.S.J. Rumondor conducted the FGD and handled research administration, J.K. Kampilong calculated all the raw data and interpreted the results, Y.S. Kawuwung prepared all the maps and tables, F.R. Tulungen analyzed the data, and E.P. Sanggelorang responsibled in interviewing to the breeders.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
^{0}C	Degree of Celsius
44/28	The value describes change in the emission value of $N_2O\text{-}N_{(mm)}$ to value $N_2O_{(mm)}$
13^{th}	Thiteenth
AD	Activity data
Arcmap	geographic information software
BPS	Central bureau of statistics
CH_4	Methane gas
CO_2	Carbon dioxide
COP	Conferences of parties
COVID-19	Corona virus disease
EF or Ef	Emission factor
EF4	Emission factor for N_2O emissions from atmospheric nitrogen deposition
FGD	Focus Group Discussion
$Frac_{Gasm}$	Percentage of managed manure N that volatilises as NH_3 dan NO_x
F	Flourine
GDP	Gross domestic products
GHGs	Greenhouse gases
Gg/y	Gigagram per year
$Gg/CH_4/y$	Gigagram methane per year
Gg/CO_2-eq/y	Gigagram carbón dioxide equivalent per year
GIS	Geographic Information System
Gt/CO_2-eq/y	gigatons carbón dioxide equivalent per year
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
MEFRI	The Ministry of Environment and Forest of the Republic of Indonesia
Kg/day	Kilograms per day
Kg/ha/day	Kilograms per hectare per day
Kg/head/y	Kilograms per head per year
$Kg/CH_4/$head/y	Kilograms CH_4 per head per year
Kg/N/animal/y	Kilograms nitrogen per animal per year
$Kg/N_2O/y$	Kilograms N_2O per year
$K_{(T)}$	Correction factor (by animal type)
$MS_{(T, S)}$	Fraction of N excreted per animal type (T) based on manure management system (S)
N	Nitrogen
N_2O	Dinitrous oxide
$N_2O_{(mm)}$	Direct N_2O from manure management
$N_2O_{G(mm)}$	Indirect emissions of N_2O resulting from evaporation of N manure management
$Nex_{(T)}$	Annual average N excretion
$N_{volatilization-}$	The amount of manure lost due to volatilization NH3 and NOX
$N_{(T)}$	Animal number by type/species
Ppb	Parts per billion
T	Animal type/species number
Tier-1	Method of GHG emission estimation (one of three methods from IPCC)
Tg/CO_2-eq/y	Tetagrams CO_2 equivalent per year
UN	United Nations
UNFCCC	United Nations Frameworks Convention on Climate Change

REFERENCES

Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I., (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res., 29: 42539–42559 **(21 pages)**.

Adzawla, W.; Sawaneh, M.; Yusuf, A.M., (2019). Greenhouse gasses emission and economic growth nexus of sub-Saharan Africa. Scientific African, 3: e00065 **(9 pages).**

Anderson, T.R.; Hawkins, E.; Jones, P.D., (2016). CO_2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's earth system models. Endeavour. 40: 3 **(10 pages)**.

Arsad, F.S.; Hod, R.; Ahmad, N.; Ismail, R.; Mohamed, N.; Baharom, M.; Osman, Y.; Mohd Radi, M.F.; Tangang, F., (2022). The impact of heatwaves on mortality and morbidity and the associated vulnerability factors: A systematic review. Int. J. Res. Public health. 19(23): 16356 **(22 pages).**

Aryal, J.P.; Sapkota, T.B.; Khurana, R.; Khatri-Chhetri, A.; Rahut, D.B.; Jat, M.L., (2020). Climate change and agriculture in South Asia: Adaptation options in smallholder production systems. In Environ. Dev. Sustainability, Springer Netherlands., 22: 6 **(31 pages)**.

BPS, (2023). Minahasa Regency in figures., (2023). BPS Kabupaten Minahasa, Central Bureau of Statistics of Minahasa Regency., **(372 pages)**.

Bradbury, J.; Zachary C.; Down, A., (2015). Greenhouse gas emissions and fuel use within the natural gas supply chain – Sankey diagram methodology. US Department of Energy, Special Report., 1–22 **(22 pages).**

Camello, J.; Mayo, T.L.; Gutmann, E.D. (2020). Projected climate change impacts on hurricane storm surge inundation in the coastal United States. Front. Built Environ., 6: 588049 **(16 pages)**.

Chang, J.; Peng, S.; Ciais, P.; Saunois, M.; Dangal, S.R.S.; Herrero, M.; Havlík, P.; Tian, H.; Bousquet, P., (2019). Revisiting enteric methane emissions from domestic ruminants and their CH_4 source signature. Nat. Commun., 10: 1 **(14 pages)**.

Chataut, G.; Bhatta, B.; Joshi, D.; Subedi, K.; Kafle, K., (2023). Greenhouse gases emission from agricultural soil: A review. J. Agric. Food Res., 11: 100533 **(8 pages)**.

Cheng, M.; McCarl, B.; Fei, C., (2021). Climate change and livestock production: A literature review. Atmos., 13(1): 140 **(20 pages).**

Chu, E.W.; Karr, J.R., (2017). Environmental impact: Concept, consequences, measurement. Ref. Module Life Sci., B978-0-12-809633-8023803 **(25 pages).**

Cohen, S.; Stanhill, G., (2020). Changes in the Sun's radiation: The role of widespread surface solar radiation trends in climate change: Dimming and brightening. Clim. Chang. (3rd Ed): 687-709 **(23 pages).**

Dietz, W.H., (2019). Climate change and malnutrition: We need to act now. J. Clin. Inves., 130 (2): 556-558 **(3 pages).**

Ding, T.; Ning, Y.; Zhang, Y., (2017). Estimation of greenhouse gas emissions in China 1990-2013. Greenh. Gases Sci. Technol., 7(6): 1097–1115 **(19 pages)**.

Dong, H.; Mangino, J.; McAllister, T.A.; Hatfield, J.L.; Johnson, D.E.; Lassey, K.R.; Aparecida de Lima, M.; Romanovskaya, A., (2006). Chapter 10: Emissions from livestock and manure management. Prepared by the National Greenhouse Gas Inventories Programme, IPCC 2006 Guidelines for national greenhouse inventories., Vol. 4 **(87 pages)**.

Eckelman, M.J.; Sherman, J., (2016). Environmental impacts of the U.S. health care system and effects on public health. PLOS ONE. 11(6): e0157014 **(14 pages).**

Fanzo, J.C.; Downs, S.M., (2021). Climate change and nutrition-associated diseases. Nat. Rev. Dis. Primers*.,* 7: 90 **(2 pages)**.

Forster, P.V.; Ramaswamy, P.; Artaxo, T.; Berntsen, R.; Betts, D.W.; Fahey, J.; Haywood, J.; Lean, D.C.; Lowe, G.; Myhre, J.; Nganga, R.; Prinn, G.; Raga, M., (2007). Changes in atmospheric constituents and in radiative forcing. In: climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the IPCC (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA **(106 pages).**

Frimawaty, E.; Ilmika, A.; Sakina, N.A.; Mustabi, J., (2023). Climate change mitigation and adaptation through livestock waste management. Global J. Environ. Sci. Manage., 9(4): 691–706 **(16 pages)**.

Gavurova, B.; Rigelsky, M.; Ivankova, V., (2021). Greenhouse gas emissions and health in the countries of the European Union. Front. Public Health. 9: 756652 **(13 pages).**

Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.,; Dijkman, J.; Falcucci, A.; Tempio, G., (2013). Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO, Rome. ISBN: 978-92-5-107920-1 (**139 pages**).

Godde, C.; Mason-D'Croz, D.; Mayberry, D.; Thornton, P.; Herrero, M., (2021). Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Secure. 28: 100488 **(17 pages).**

Grossi, G.; Goglio, P.; Vitali, A.; Williams, A.G., (2019). Livestock and climate change: Impact of livestock on climate and mitigation strategies. Anim. Front., 9(1): 69-76 **(8 pages).**

Guo, H.; Su, Z.; Yang, X.; Xu, S.; Pan. H., (2022). Greenhouse gas emissions from beef cattle breeding based on the ecological cycle model. Int. J. Environ. Res. Public Health., 19(15): 9481 **(15 pages)**.

Jayanegara, A.; Makkar, H.P.S.; Becker, K., (2009). Emisi metana dan fermentasi rumen in vitro ransum hay yang mengandung tanin murni pada konsentrasi rendah. Trop. Anim. Sci. J., 32: 3 **(11 pages)**.

Konapala, G.; Mishra, A.K.; Wada, Y.; Mann, M.E., (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nat. Commun., 11(1): 1-10 **(10 pages)**.

Kushawaha, J.; Borra, S.; Kushawaha, A.K.; Singh, G.; Singh, P., (2020). Climate change and its impact on natural resources. Water Conservation in the Era of Global Clim. Chang. 333-346 **(14 pages).**

Kweku, D.; Bismark, O; Maxwell, A.; Desmond, K.; Danso, K.; Oti-Mensah, E.; Quachie, A.; Adormaa, B., (2018). Greenhouse effect: Greenhouse gases and their impact on global warming. J. Sci. Res. Rep., 17: 1-9 **(9 pages).**

Liu, J.; Varghese, B.M.; Hansen, A.; Zhang, Y.; Driscoll, T.; Morgan, G.; Dear, K.; Gourley, M.; Capon, A.; Bi, P., (2022). Heat exposure and cardiovascular health outcomes: A systematic review and meta-analysis. The Lancet Planet.

Health. 6(6): e484-e495 **(12 pages).**

Malik, A.; Arief, M.; Withaningsih, S.; Parikesit, P., (2023). Modeling regional aboveground carbon stock dynamics affected by land use and land cover changes. Global J. Environ. Sci. Manage., 10(1): 1-22 **(22 pages).**

Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E., (2020). Environmental and health impacts of air pollution: A review. Front. Public Health. 8: 505570 **(13 pages).**

MEFRI, (2019) Report of Indonesia GHG Inventory and Monitoring, Reporting, Verification (MRV) – 2019. Ministry of Environment and Forest of the Republic of Indonesia, Kementrian Lingkungan Hidup dan Kehutanan RI. Jakarta., V: 7 (**142 pages**).

MEFRI, (2022). Report of Indonesia GHG Inventory and Monitoring, Reporting, Verification (MRV) - 2021, Kementrian Lingkungan Hidup dan Kehutanan RI. Jakarta 2021., Vol. 7 **(176 pages)**.

Min, B.; Lee, S.; Jung, H.; Miller, D.N., (2022). Enteric methane emissions and animal performance in dairy and beef cattle production: strategies, opportunities, and impact of reducing emissions. Animals. 12: 948 **(27 pages)**.

Mirzabaev, A.; Bezner Kerr, R.; Hasegawa, T.; Pradhan, P.; Wreford, A.; Cristina Tirado von der Pahlen, M.; Gurney-Smith, H., (2022). Severe climate change risks to food security and nutrition. Clim. Risk Manage., 39: 100473 **(10 pages).**

Montes, F.; Meinen, R.; Dell, C.; Rotz, A.; Hristov, A.N.; Oh, J.; Waghorn, G.; Gerber, P.J.; Henderson, B.; Makkar, H.P.S.; Dijkstra, J., (2018). Special topics-Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. J. Anim. Sci., 91: 11 **(25 pages)**.

Orzuna-Orzuna, J.F.; Dorantes-Iturbide, G.; Lara-Bueno, A.; Mendoza-Martínez, G.D.; Miranda-Romero, L.A.; Hernández-García, P.A., (2021). Effects of dietary tannins' supplementation on growth performance, rumen fermentation, and enteric methane emissions in beef cattle: A meta-analysis. Sustainability. 13: 13 **(27 pages)**.

Panchasara, H.; Samrat, N.H.; Islam, N., (2021). Greenhouse gas emissions trends and mitigation measures in Australian agriculture sector: A review. Agric., 11(2): 85 (**16 Pages**).

Parra, A.S.; de Figueiredo, E.B.; de Bordonal, R.O.; Moitinho, R.L.; de Bortoli, D.T.; La Scala Jr, N. (2019). Greenhouse gas emissions in conversion from extensive pasture to other agricultural systems in the Andean region of Colombia. Environ. Dev. Sustainable. 21: 249–262 (**14 pages**).

Purohit, J.; Rout, H.S., (2023). Impact of climate change on human health concerning climate-induced natural disaster: Evidence from an eastern Indian state. Clim. Change. 176(8): 109 (**7 pages**).

Rahman, M.H.; Ahmad, A.; Raza, A.; Hasnain, M.U.; Alharby, H.F.; Alzahrani, Y.M.; Bamagoos, A.A.; Hakeem, K.R.; Ahmad, S.; Nasim, W.; Ali, S., Mansour, F.; EL Sabagh, A. (2022a). Impact of climate change on agricultural production: Issues, challenges, and opportunities in Asia. Front. Plant Sci., 13: 925548 **(22 pages).**

Rahman, T.; Candolin, U., (2022b). Linking animal behavior to ecosystem change in disturbed environments. Front. Ecol. Evol., 10: 893453 **(13 pages).**

Robock, A. (1990). The volcanic contribution to climate change of the past 100 years. Dev. Atmos. Sci., 19: 429-443 **(15 pages).**

Rocha, J.; Oliveira, S.; Viana, C.M.; Ribeiro, A.I., (2022). Chapter 8 - Climate change and its impacts on health, environment and economy. One Health, Academic Press. 253-279 **(26 pages).**

Roque, B.M.; Venegas, M.; Kinley, R.D.; Duarte, T.L.; Yang, X.; Kebreab, E., (2021). Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. Plos One. 16(3): e0247820 **(20 pages)**.

San Martin Ruiz, M.; González Puelles, J.E.; Herra Bogantes, J.; Rivera-Méndez, W.; Reiser, M.; Kranert, M., (2022). Methane, Nitrous Oxide, and Ammonia emissions on dairy farms in Spain with or without bio-activator treatment. Atmos., 13 (6): 893 **(15 pages)**.

Tang, Y.H.; Luan, X.B.; Sun, J.X.; Zhao, J.F.; Yin, Y.L., (2021). Impact assessment of climate change and human activities on GHG emissions and agricultural water use. Agric. For. Meteorol., 29: 108218 **(13 pages)**.

UN, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision, key findings and advance tables. Working Paper. No: ESA/P/WP/248 **(53 pages)**.

UNEP. Governing Council (15th sess.: 1989: Nairobi) (1989). Global climate change. Adopted at the 12th meeting, 25 May 1989. In: United Nations Environment Programme: report of the Governing Council on the work of its 15th session, 15-26 May 1989., A/44/25: 164-168 **(5 pages).**

Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Jevrejeva, S.; Jackson, L.P.; Feyen, L., (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat. Commun., 9(1): 1–12 **(12 pages)**.

Winter, M.G.; Peeling, D.; Palmer, D.; Peeling, J., (2019). Economic impacts of landslides and floods on a road network. AUC Geographica. 54 (2): 207-220 **(14 pages).**

Yamaka, W.; Phadkantha, R.; Rakpho, P., (2021). Economic and energy impacts on greenhouse gas emissions: A case study of China and the USA. Energy Rep., 7: 240-247 **(8 pages).**

Yasmin, N.; Jamuda, M.; Panda, A.K.; Samal, K.; Nayak, J.K., (2022). Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. Energy Nexus. 7: 100092 **(16 pages)**.

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CASE STUDY

Enhancing coastal community participation in mangrove rehabilitation through structural equation modeling

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ABSTRACT

BACKGROUND AND OBJECTIVES: Mangroves are unique plants distributed in tropical regions, such as Indonesia. Mangrove areas and various mangrove ecosystems have been lost in the past decades. The purpose of this study is to investigate community participation using structural equations modeling to enhance involvement in mangrove forest rehabilitation. The study was conducted in two sub-districts in East Lampung Regency, Lampung Province.
METHODS: The study employed a survey method with quantitative descriptive analysis and Structural Equation Models analysis. The sampling method used was simple random sampling. The community under investigation is a part of the mangrove forest management group in Labuhan Maringgai and Pasir districts, Lampung, Indonesia. The total number of individuals who are members of the mangrove forest management group is 292, distributed with 140 in Margasari and 152 in Pasir Sakti District. The sample size in Margasari District was 81 respondents, and in Pasir Sakti, it was 87 respondents, totaling 168 respondents. The sample size determination was based on the Slovin formula, considering a precision of 5 percent when estimating the proportion of the population.
FINDINGS: This study's results show that the level of community participation in mangrove forest rehabilitation still falls within the low category, particularly in planning and evaluation, while implementation is categorized as medium. Community leaders often possess influence and authority that is recognized by community members. When these leaders actively support mangrove conservation, they can influence the opinions and actions of the entire community. In this capacity, they serve as role models, inspiring others to participate in mangrove conservation activities. Community participation includes planning, implementation, evaluation, and utilization of results. Participation influences welfare: the more active the community, the more space there will be to utilize mangrove products and interact with other community members, so that income, needs for food, and adequate housing can be met. Local working groups or initiatives that focus on mangrove conservation coordinate field activities and organize necessary resources and manpower.
CONCLUSION: The role of community leaders, farmer groups, government support, and non-government organizations plays a key role in increasing community participation in mangrove forest rehabilitation. Additionally, the increase in non-formal education (training and mentoring), type of work, number of family dependents, length of residence, and distance to the mangrove location are crucial factors in enhancing community involvement.

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INTRODUCTION

Mangroves are highly productive forests, encompassing both natural and non-natural mangrove environments. Mangroves are known for secondary metabolites such as amino acids, macro and micro nutrient, tannin content and proximate content (Ariyanto *et al.,* 2018a; Ariyanto *et al.,* 2019a; Ariyanto *et al.,* 2019b; Ningsih *et al.,* 2020). Mangroves are also recognized for their antimicrobial, antibacterial, and antifungal potency (Pringgenies *et al.,* 2021; Pringgenies *et al.,* 2023). Moreover, they can be utilized for carbon storage and sequestration (Hartoko *et al.*, 2015; Sigh *et al.,* 2023; Nwankwo *et al.,* 2023). Mangroves contribute to the food source for marine biota (Ariyanto, 2019) and harbor gastropod biodiversity (Ariyanto *et al.,* 2018b; Ariyanto *et al.,* 2020). Spalding and Arrett (2019) also revealed that mangroves can be utilized for tourism through activities such as exploration, facilities, and the appreciation of key species within mangrove ecosystems. Moreover, mangroves require a synergistic approach and other key elements in an action plan, including the control and regulation of destructive economic activities (Barbier *et al.,* 2011) and the dynamics of litter production (Ariyanto *et al.,* 2019c). Mangrove degradation is linked to livelihoods in fisheries and environmental services (Sadono *et al.,* 2020). In addition sustainability of mangrove forests has received positive perceptions from local communities (Setiyaningrum, 2019). The success of mangrove rehabilitation significantly affects the ecological, social, and economic values of coastal communities (Ellison *et al.,* 2020; Takrina *et al.,* 2023) combining both social and ecological parameters (Budiharta *et al.,* 2016). Chamberland-Fontaine *et al. (*2022) also reported that collaborative governance can systematically enhance the collaboration process. Djosetro and Behagel (2020) reported that open dialogue and local leadership are needed to manage natural resources. East Lampung Regency is a district that has 24 sub-districts, and there are 2 sub-districts that have mangrove forests: Labuhan Maringgai District and Pasir Sakti District. These two sub-districts have the largest mangrove forests compared to others in East Lampung Regency. The increased area of mangrove forests, apart from being influenced by environmental factors, is also influenced by community participation in preserving the environment around mangrove forests. As the area of mangroves increases, the potential for utilizing mangrove resources also increases. Labuhan Maringgai District and Pasir Sakti District have great potential in preserving and utilizing mangrove forests. Mangrove forest conservation in these two sub-districts has been initiated since 2005; therefore, the condition of the mangrove ecosystem is not damaged; however, community participation is needed for mangrove rehabilitation. This study was conducted in Lampung Province and consisted of the Pasir Sakti sub-district. The mangrove area from 2019 to 2021 increased from 350 ha to 374 ha, reflecting a 24-ha increase. This is not significantly different from the mangrove forest in Margasari sub-district, which also experiences yearly increases in forest area. Local communities can play a crucial role in protecting mangrove forests through policy and legislative measures (Taher *et al.,* 2023). However, the conservation of mangrove forests may face challenges, such as marginalizing key stakeholders (Gayo, 2022). To address this, strategic collaboration between institutions is deemed critical for ensuring sustainable rehabilitation (Damastuti *et al.,* 2023). Through community participation in managing and preserving mangrove forests, awareness of the surrounding environment can be heightened. At the end of 2004, a major tsunami disaster occurred, inspiring some individuals and the government about the significance of mangrove forests as natural fortifications against large waves. Additionally, mangrove forests serve as a habitat for the growth and development of various types of marine biota. However, presently, many people are cutting down mangrove forests to create ponds, despite the threat of criminal penalties awaiting them. Based on this explanation, this study aims to identify the best model for developing strategies to increase community participation in mangrove forest rehabilitation in East Lampung Regency in 2023.

MATERIALS AND METHODS

Materials

The survey method was employed to collect samples from the population in Labuhan Maringgai and Pasir Districts (Fig. 1.). Pasir Sakti District is geographically situated at 50°28’29.30” South Latitude 50°37’15.41” South Latitude and 105°42’58.27” East Longitude 105°49’21.30” East Longitude and experiences a tropical climate. The members of the mangrove

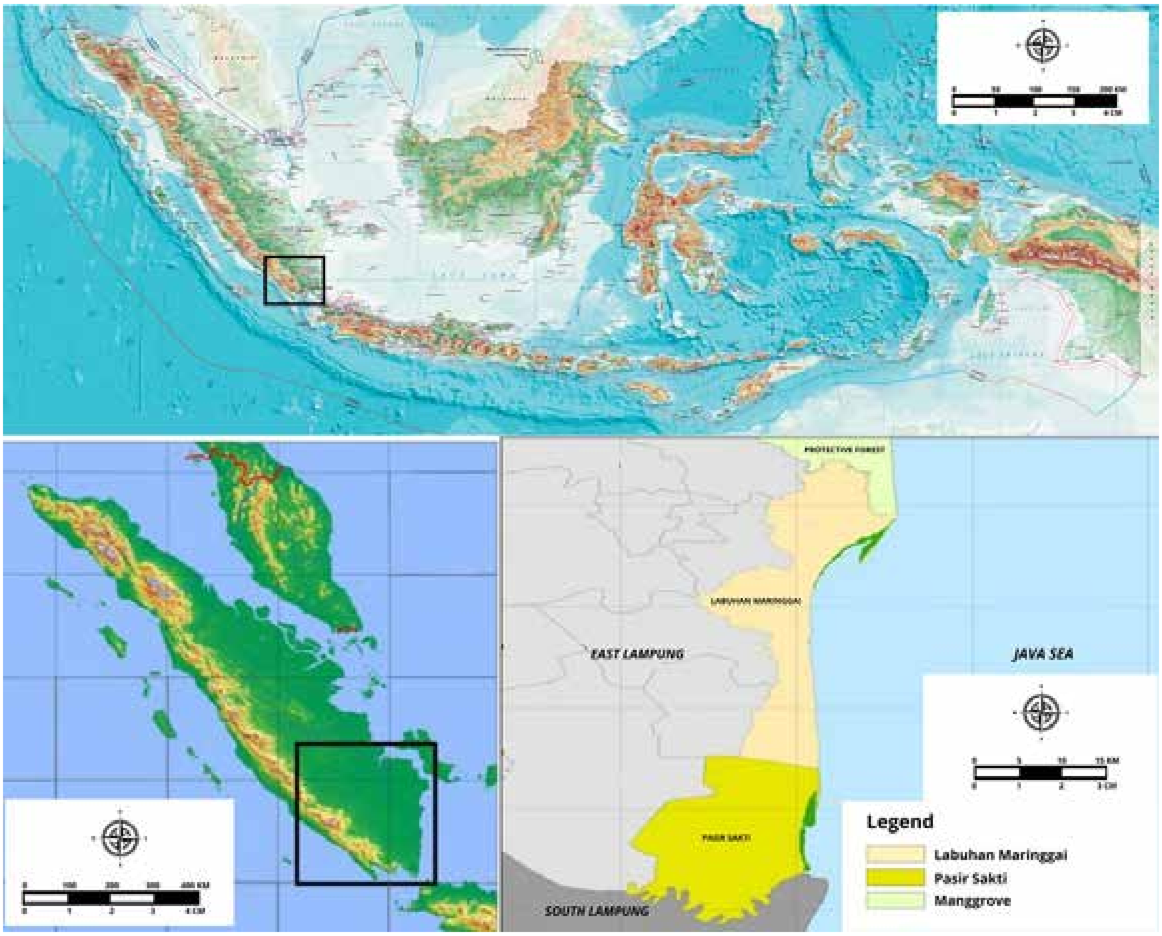


Fig. 1: Geographic location of the study site research, Labuhan Maringgai District and Pasir Sakti District, Lampung, Indonesia

forest management group are 292 people, with a distribution of 140 people in Margasari and 152 people in Pasir Sakti District. The number of samples in Margasari District was taken as 81 respondents, and the number of samples in Pasir Sakti was taken as 87 people, for a total sample of 168 respondents. This was determined using the Slovin formula based on estimating the proportion of the population with a precision consideration of 5 percent. The number of respondents in this study was 168, determined using the Slovin formula from a population of 292. The sampling method in this study employed a simple random sampling method. Questionnaires are created in various formats, either as answer choices illustrating the ranking of responses or in the form of a Likert scale. In a questionnaire featuring a Likert scale, several alternative answers are provided for each statement item, and respondents select the option that aligns with their experiences.

Data collection

The collected data were analyzed using both descriptive statistics and inferential statistics. To offer an overview of individual characteristics (X1), the role of community leaders (X2), the role of farmer groups (X3), government support (X4), NGO support (X5), community participation in mangrove rehabilitation (Y), and the level of welfare (Z), descriptive analysis was conducted employing frequency distribution tables. Meanwhile, to address the second objective, Structural Equation Model (SEM) analysis was employed. The purpose of SEM analysis was to estimate the population (generalization), examining the extent to which independent variables influence dependent variables, and assessing the compatibility of the study's designed model (hypothetical model) with the real model. The strategy forming was based on the results of SEM analysis. According to Fan *et al.* (2016), SEM is a multivariate data analysis method designed to test measurement models and latent variable structural models. Three main characteristics of SEM can be identified, addressing its limitations:

(1) SEM is a combination of interdependence and dependence multivariate data analysis techniques, specifically confirmatory factor analysis and path analysis.

(2) The variables analyzed in SEM are latent variables (constructs), which are variables that cannot be directly observed (unobservable) but are measured through measurable indicators known as manifest variables.

(3) SEM does not aim to produce models but rather to analyze or confirm theory-based models, specifically measurement models and structural models.

Consequently, there are at least two research problems addressed through SEM:

(1) Descriptive research problems are concerned with describing or empirically confirming the conformity of construct models or "theoretical or hypothetical constructs," viewed according to indicators conceptualized as manifests of the construct.

(2) The problem of explanatory research involves explaining causal relationships between latent variables; this second problem is named the structural model.

Data processing and analysis utilized the SPSS (Statistical Product and Service Solution) version 21 and LISREL (Linear Structural Relationships) 8.8 programs. Qualitative data were employed to provide an explanation of the quantitative data. SEM was conducted using Eq. 1 (Stein *et al.,* 2011).

$$\eta = B_{\eta} + \tilde{\Gamma}\xi + \zeta \qquad (1)$$

Where;

η = eta, a vector of endogenous variables (latent variable Y)

B = beta (large), a coefficient matrix that describes the influence of other endogenous variables

Γ̃ = gamma (large), a coefficient matrix that describes the influence of exogenous variables on endogenous variables

ξ = xi, a vector of exogenous variables (latent variable X)

ζ = zeta, a vector of residuals or errors in the equation

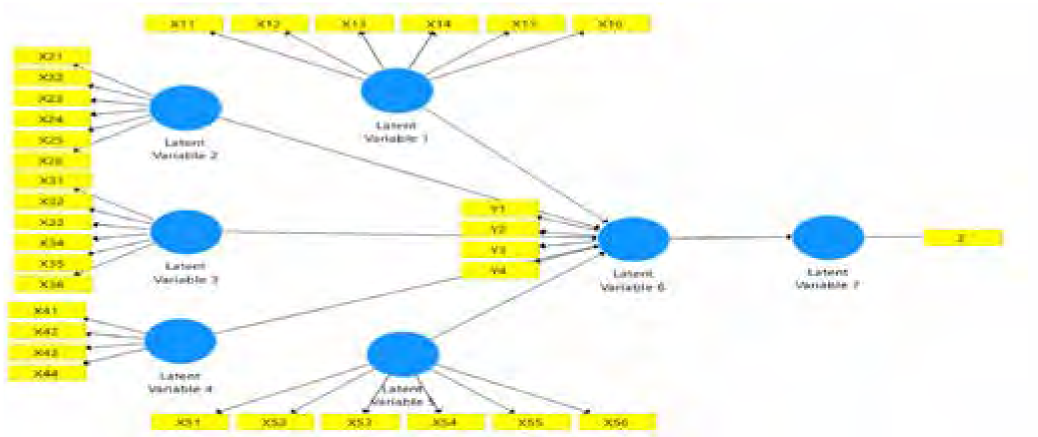
SEM is used to describe a system of linear equations for testing the suitability of the hypothesized "causal" model. Therefore, the initial step involves visualizing the hypothesized model or creating a "path diagram" based on previous theoretical studies. The visualization of the path diagram is presented in 2a and 2b. Both 2a and 2b do not have differences, with the only variation being the placement of Y, changed from being parallel to Z to a vertical position between Y and Z. (Fig. 2a. and Fig. 2b.).

Descriptive analysis is employed to address the initial objective; this analysis solely reveals the extent of participation and distribution of individual characteristics, markedly distinct from SEM analysis. SEM analysis is utilized to identify the best indicators for constructing models. In SEM analysis, if multiple variables and indicators lack influence, they can be eliminated from the structural equation model. The Likert scale was utilized in this study as a closed question type, and the data type utilized for this investigation is ordinal data. Data tabulation was employed to gather responses from the participants. The Smart PLS application, along with SEM analysis, was utilized to process the data. The Likert scale was utilized in this study as a closed question type. The data type used for this investigation is ordinal data. In this study, data tabulation was utilized to collect responses from respondents. The Smart PLS application with SEM analysis is used to process the data.

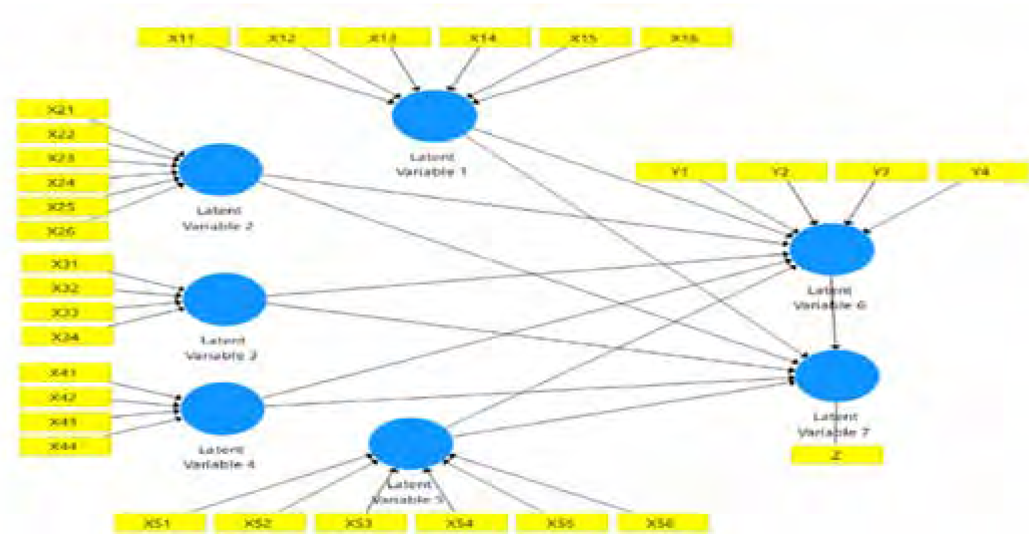
RESULTS AND DISCUSSION

Individual characteristics (X1)

Indicators of individual characteristics encompass age, level of formal education, level of non-formal education, number of family dependents, length of residence, and distance to the mangrove forest (Table 1). The three defined categories based on value include low (corresponding to the smallest score or bottom value), middle (spanning the range between the highest and lowest values), and high



(a)



(b)

Fig. 2: Initial model of strategy to increase the participation of coastal communities in mangrove rehabilitation (a) the first structural equation modeling (b) the second structural equation modeling.

(reflecting the biggest score or top value). The distribution of respondents by age group ranged from 19 to 72 years. The average respondent in the study was 42 years old, falling within the productive age category. Individuals in this age range typically possess good physical ability to engage in various activities, including participation in mangrove rehabilitation. Moreover, older communities remain active and eager about involvement in mangrove conservation. Elderly individuals, who bring more experience and knowledge, tend to feel satisfied with their achievements (Inayat and Jahanzeb Khan, 2021). Guo *et al*. (2015) revealed that training and policy development are necessary to alter the age at which farmers engage in regeneration. Other research has also suggested that farmers require education to effectively compete in a liberal economy (Fielke and Bardsley, 2014). All respondents in the study location have received education and have experience, enabling them to think critically and hold viewpoints on preserving mangrove forests. Most of the respondents had education at the junior high

Table 1: Individual characteristic

No	Characteristics	Classification	Class(score)	Number of people	%
1	Age	Unproductive	0-14	0	0.00
	Average	Productive	15-64	163	97.02
	42 years old	Non-Productive	>65	5	1.41
2	Formal Education	Elementary School	6 years	27	16.07
		Middle School	9 years	65	38.69
		High School	12 years	62	36.90
		University	More than 14 years	14	8.33
3	Non-formal Education	Low	0-1 times	92	54.76
		Middle	1-2 times	59	35.12
		High	2-3 times	17	10.12
4	Number of Family 3 people	Low	0-2 people	60	35.71
		Middle	2-4 people	89	52.98
		High	4-6 people	17	11.31
5	Length of Stay 27,2 years	Low	11-32 years	110	65.48
		Middle	33-52 years	55	32.74
		High	53-72 years	3	1.79
6	Distance to Mangrove 2.32 kilometer (km)	Low	1-2 km	93	55.36
		Middle	2-3 km	45	26.79
		High	3-4 km	30	17.86

school level as 38 percent (%) and high school level (36%). Less than 10% of respondents had higher education. Formal education is considered one of the efforts to increase knowledge and change the mindset of individuals, as well as to help extension agents advance in their careers (Listiana *et al.,* 2019). Formal education serves to develop abilities, improve the quality of life, and enhance human dignity both individually and socially (Phiri *et al.,* 2020; Bellaire *et al.,* 2023).

Most respondents (61.29%) have attended non-formal education or training related to mangroves, with the majority (61.29%) having participated in training 1–2 times. The non-formal education encompasses seminars, training, and socialization related to mangrove conservation. Non-formal education can enhance people's practical skills in mangrove conservation, thereby strengthening their participation and having a greater impact. The more farmers participate in extension activities, the higher the success of the extension services delivered, subsequently increasing their knowledge (Antwi-Agyei and Tringer, 2021). The length of stay is the duration a person has lived in the area or the length of time people have inhabited an area. The respondents' length of stay was ranked between 11 and 32 years, comprising 65.48%, with an average of 27.2 years. Through participation in community activities, such as environmental conservation groups or local community organizations, communities can actively contribute to mangrove conservation efforts (Arifanti *et al.,* 2022).

The role of community leaders (X2)

Community leaders wield extensive influence and authority in society, actively leading, guiding, and influencing community direction and policy (Table 2). The role of a public figure refers to the role played by individuals in a group or community. As a result, these individuals were motivated to play a role in protecting mangrove resources. They expressed the urgent need for a new strategic approach to recover and conserve the resources, leading to the creation of the community network. The role of community leaders falls within the middle category; some people believe that community leaders have performed their duties and functions quite well. The role of community leaders is crucial in mobilizing community participation in mangrove conservation through motivation and inspiration, information delivery, education and training, as well as collaboration with opinion leaders. The presence of community leaders

Table 2: Level of community leaders' role

No	Statement	Classification	Number of People	%
X2	Role of Community Leaders	Low (7-10)	39	23.21
		Middle (11-14)	76	45.24
		High (15-18)	53	31.55
	Average (13.28)	Middle		
X21	Community leaders monitor RHL	Low	27	16.07
		Middle	70	41.67
		High	71	42.26
X22	Community leaders invite the community to take part in the RHL program	Low	23	13.69
		Middle	90	53.57
		High	55	32.74
X23	Community leaders provide information regarding the RHL program	Low	12	7.14
		Middle	63	37.50
		High	93	55.36
X24	Community leaders provide support in implementing the RHL program	Low	20	11.90
		Middle	73	43,45
		High	75	44,64
X25	Community leaders provide rewards/witnesses to RHL perpetrators	Low	46	27.38
		Middle	81	48.21
		High	41	24.40
X26	Community leaders set an example for preserving forests	Low	47	27.98
		Middle	65	32.34
		High	56	27.86

who support and are actively involved can positively influence communities to participate in mangrove conservation efforts.

The role of farmer groups (X3)

Table 3 shows the role of farmer groups in empowering their members. This role involves a series of activities and functions carried out by farmer groups, serving as a vehicle for learning, organization, cooperation, and as a forum for production units dedicated to learning. Farmer groups can serve as agents of community empowerment in mangrove conservation by providing education, training, and information to group members and local communities about the importance of mangroves and how to maintain their sustainability. In addition, farmer groups can mobilize their members and other communities to participate in mangrove conservation activities, such as mangrove tree planting programs or cleaning mangrove areas, by providing facilities and infrastructure. Farmer groups support the information flow and contribute to the best performance (Fischer and Qaim, 2012; Abdul-Rahaman and Abdulai, 2020).

Government support

Government support involves the involvement of the government apparatus in mangrove conservation. The indicators utilized include facilities, policies, guidance, and financing, which are then classified (Table 4). Mangrove conservation efforts in the community of Purworejo Village, Pasir Sakti District, according to respondents' assessments, have only received government support in terms of funding and supervision, extending from the neighborhood harmony level to the village. Additionally, the community has also contributed support. Through government policies, a legal basis for mangrove protection and management can be established. With regulations in place, the community will feel more encouraged to participate in mangrove conservation efforts and comply with existing rules. The government can encourage the empowerment of local communities in mangrove conservation through training programs, skill development, and authorization (Sam *et al.,* 2023). To support mangrove rehabilitation in Indonesia, the government is implementing the Mangrove for coastal resilience

Table 3: Level of farmer groups' role

No.	Statements	Classification	Number of people	%
X3	The Role of Famer Groups	Low (4-6)	44	26.19
		Middle (7-9)	50	29.76
		High (10-12)	74	44.05
	Average (8.85)	Middle		
X31	The place to learn	Low	32	19.05
		Middle	32	19.05
		High	104	61.90
X32	The place to organize	Low	32	19.05
		Middle	77	45.83
		High	59	35.12
X33	The place to collaboration	Low	39	23.21
		Middle	64	38.10
		High	65	38.69
X34	The place to production unit	Low	38	22.62
		Middle	73	43.45
		High	57	33.93

Table 4: Level of government support

No.	Statement	Classification	Number of People	%
X4	Government Support	Low (5-7)	34	20.24
		Middle (8-10)	100	59.52
		High (11-12)	34	20.24
	Average (9,16)	Middle	-	-
X41	The government provides policies to regulate mangrove forest conservation.	Low	21	12.50
		Middle	85	50.60
		High	62	36.90
X42	The government provides funding support for the RHL program	Low	18	10.71
		Middle	67	39.88
		High	83	49.40
X43	The government provides assistance/counseling regarding the RHL program	Low	17	10.12
		Middle	68	40.48
		High	83	49.40
X44	Rewards/Punishments from the government are given to RHL program participants	Low	23	13.69
		Middle	99	58.93
		High	46	27.38

(M4CR) program. This study can furnish valuable insights for the government to formulate suitable strategies aimed at enhancing community engagement in mangrove forest rehabilitation. As community participation in mangrove rehabilitation grows, so too will the resilience of the mangrove forest ecosystem.

The role of non-governmental organizations

Non-governmental organizations (NGOs) play a crucial role in encouraging community participation in mangrove conservation through education, community engagement, monitoring, advocacy, and collaboration with the government and other institutions. The beneficiaries of mangrove rehabilitation are the surrounding communities; however, this does not preclude the opportunity for outsiders to participate in mangrove rehabilitation. The involvement of NGOs in community empowerment programs entails a significant level

Table 5: Level of non-government organization' role

No.	Statement	Classification	Number of people	%
X5	Non-Government Organization	Low (8-11)	38	22.62
		Middle (11-14)	90	53.57
		High (14-17)	40	23.81
	Average (12.92)	Middle	-	-
X51	Contribute ideas about managing the RHL program	Low	18	10.71
		Middle	114	67.86
		High	36	21.43
X52	Provide assistance in managing the RHL program	Low	35	20.83
		Middle	61	36.31
		High	72	42.86
X53	Provide assistance/counseling regarding the RHL program	Low	5	2.98
		Middle	107	63.69
		High	56	33.33
X54	Involved in RHL program planning	Low	36	21.43
		Middle	80	47.62
		High	52	30.95
X55	Involved in implementing the RHL program	Low	19	11.31
		Middle	80	47.62
		High	69	41.07
X56	Involved in RHL program evaluation	Low	60	35.71
		Middle	64	38.10
		High	44	26.19

of active community participation (Table 5). The beneficiaries of mangrove rehabilitation are the surrounding communities; however, it does not preclude the opportunity for outsiders to participate in mangrove rehabilitation. The involvement of NGOs in community empowerment programs includes significant active community participation. NGOs are frequently engaged in education and environmental awareness activities related to mangrove conservation. For example, they organize educational programs about the importance of mangroves, the threats they face, and the benefits of conservation. Since community participation in mangrove rehabilitation is in the low category (49.75%), there is still a lot of room for improvement. In the Non-formal education variable, the significance value is 0.29, indicating a relationship between non-formal education and community participation. However, respondents' responses are in the low category (54.76%), showing that the majority of people have only been there once or have never received training, workshops, or related education on mangrove rehabilitation. The government can enhance existing programs to increase community participation. Personal approaches, socialization, training or workshops, routine supervision, as well as financial assistance, are suggested to improve the effectiveness of the planned programs.

Level of community participation in mangrove conservation

Mangrove conservation efforts involve various forms of actions taken to protect and maintain the sustainability of mangrove ecosystems. Community participation in mangrove conservation involves a comprehensive process that includes planning, implementing, evaluating, and utilizing the results, as depicted in Table 6. Notably, community-based mangrove management (CBMM) plays a crucial role in enhancing mangrove resource management and livelihoods (Damastuti and Groot, 2017). Additionally, Datta *et al.* (2012) highlight that socio-political and institutional factors can be influenced within the CBMM framework.

Table 6: Level of community participation in mangrove conservation

Component	Classification	Number of people	%
	Low	33	19.64
Community participation	Middle	116	69.05
	High	19	11.31
	Low	122	72.62
Planning	Middle	34	20.24
	High	12	7.14
	Low	22	13.10
Implementing	Middle	100	59.52
	High	46	27.38
	Low	59	35.12
Evaluating	Middle	98	58.33
	High	11	6.55
	Low	14	8.33
Result Utilizing	Middle	79	47.02
	High	75	44.64

Planning

Planning in mangrove rehabilitation involves determining the number of mangroves to be planted, the area of land to be planted, planting locations, planting time, and securing funding. However, some communities are not actively engaged in this process. The low participation of the community in planning can be observed through their reduced activity in submitting proposals related to mutual assistance and mangrove planting. Decisions regarding mangrove rehabilitation are predominantly made by community leaders and group administrators. To enhance livelihoods and promote sustainable management, local communities can increase their engagement and support (Mbeche *et al.,* 2021).

Implementing

The implementation of conservation involves activities such as mangrove planting, encompassing site selection, the right selection of mangrove types, and direct planting. The management and maintenance of mangrove conservation pertain to the community's role in overseeing and sustaining mangroves post-planting. Tasks include pruning, monitoring plant growth, cleaning designated areas, and protecting animals residing in mangroves, as outlined in Table 6. The overall implementation stage of mangrove conservation implementation indicators falls within the medium category on average.

Evaluating

Evaluation activities are related to the assessment of the impact of activities that have been carried out previously. The community is involved in assessing the impact of mangrove conservation activities on both the environment and local communities. Community participation in Labuhan Maringgai and Pasir Sakti subdistricts is classified as low, primarily because it relies solely on existing programs without significant personal awareness from the community. Ideally, if the community actively participates in mangrove rehabilitation, the resilience of the mangrove ecosystem can increase, thereby positively impacting community welfare. Monitoring activities can be tailored to local needs, aspirations, and capacities for forest restoration, providing accountability, scalability, and adaptability in the process (Evans *et al.,* 2018).

Structural equation testing increase community participation in mangrove rehabilitation

This test was conducted to identify the best strategy for increasing participation and to analyze factors thought to influence community participation in mangrove conservation. The community believes that government support for mangrove rehabilitation has not been optimal, and not all communities fully understand the importance of mangrove forests. Some individuals still open mangrove forests for use as ponds. To develop a model for determining the right strategy to increase community participation, it is essential to identify the main factors influencing community involvement. The factors influencing community capacity include X3, the role of figures;

X3, the role of farmer groups; X4, government support; and X5, NGO involvement. The welfare of the community is affected by Y, community involvement in mangrove rehabilitation. The results of hypothesis testing can clearly be seen in Fig. 3. The SEM analysis test results are clearly presented in the goodness-of-fit model testing table (Table 7). The final result of the structural model constitutes the answer to the study problem or hypothesis proposed, specifically predictions regarding causal relationships or influences between variables. Overall, to examine the direct and indirect influence between variables, the study performed a decomposition of the influence among variables. The decomposition of influence between

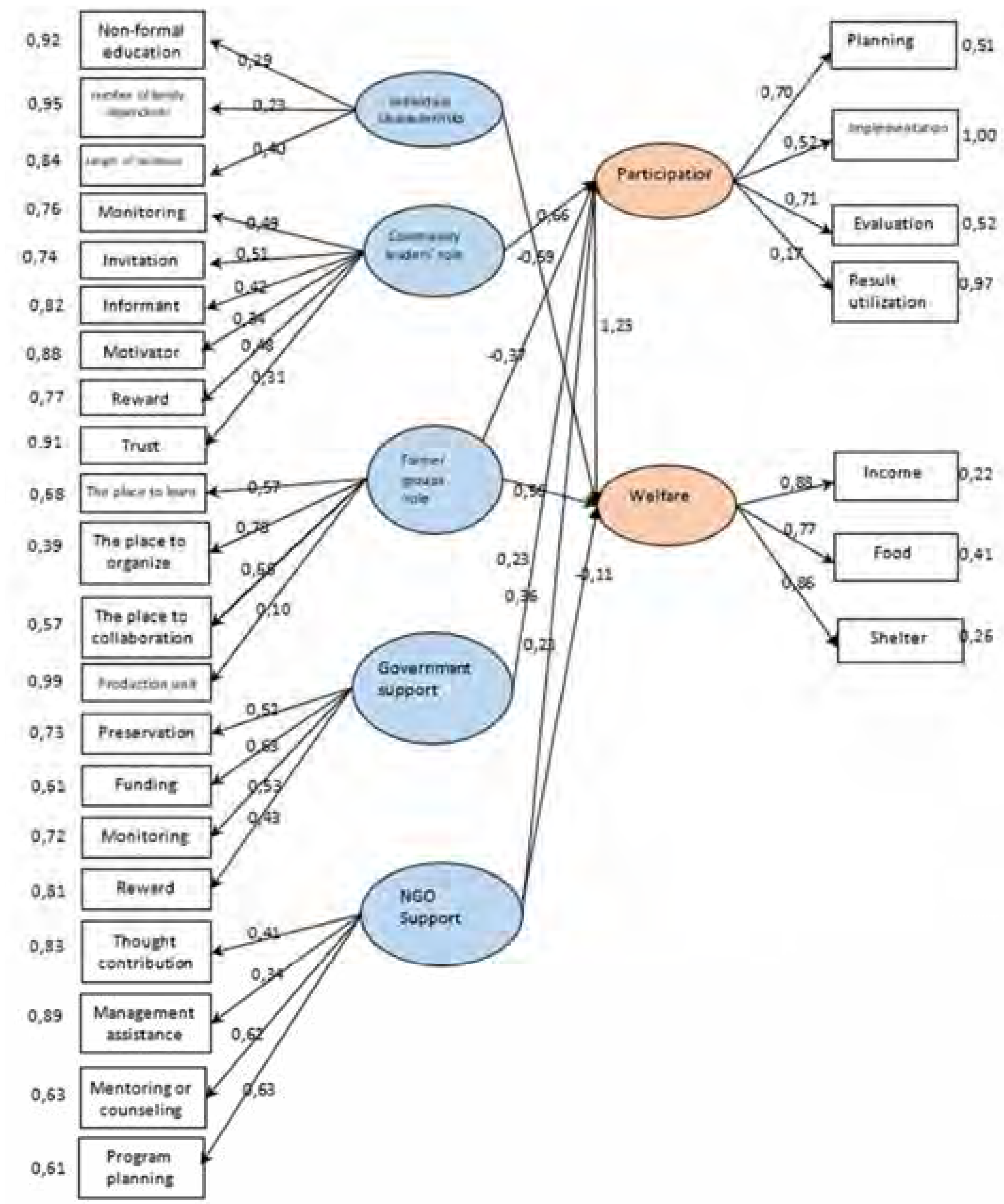


Fig. 3: Structural model of increasing community participation

Table 7: The goodness of fit model testing

Goodness-of-fit	Cut of value	Result	Conclusion
RMSEA	0,05≤RMSEA≤0.08	0.074	*good fit*
GFI	≥ 0.90	0.79	*fit*
AGFI	≥ 0.90	0.74	*fit*
CFI	≥ 0.90	0.83	*fit*
IFI	≥ 0.90	0.83	*fit*
NFI	≥ 0.90	0.73	*Fit*
NNFI	≥ 0.90	0.81	*fit*

Table 8: SEM model estimation results

Variables influence	Standardized loading factor	|t-hit| > 1.96	Conclusion
X_2 The Role of Community Leaders à Y Community Participation	0.66	2.78	Significant
X_3 The Role of Farmers Group à Y Community Participation	-0.37	-2.33	Significant
X_4 Government Support à Y Community Participation	0.36	1.32	Significant
X_5 NGOs' Support à Y Community Participation	0.23	1.14	Significant
X_1 Individual Characteristic à Z Income	-0.59	-1.48	Significant
X_3 The Role of Farmers Group à Z Income	0,56	1,37	Significant
X_5 NGOs' Support à Z Income	-0,11	-0,33	Significant
Y Community Participation à Z Income	1.23	2.73	Significant

variables involves separating the total influence into direct and indirect influences. Direct influence represents the impact of an independent variable on the dependent variable without going through any other variable. The influence of an indirect variable indicates the influence of an independent variable on a bound variable, occurring through one or more other variables conceptualized as intermediate variables. Drawing from the structural model parameter estimation image, one can elucidate the direct and indirect influences between the variables tested in the study. Table 8 presents a brief summary of the causal relationship between the study's latent variables, along with t-values as statistical tests.

SEM constitutes a flexible and comprehensive methodology for representing, estimating, and testing a theoretical model with the objective of explaining as much variance as possible. Referred to as causal models with a prominent presence in the field of consumer psychology, SEM allows for complex modeling of correlated multivariate data to elucidate interrelationships among observed and latent variables (Ramlal, 2016). This study employed SEM to analyze the factors associated with public participation in mangrove rehabilitation. (Fig. 3). The SEM analysis test results are clearly presented in the goodness-of-fit model testing (Table 7). The final result of the structural model provides the answer to the study problem or hypothesis proposed, specifically predictions about causal relationships or influences between variables.

Overall, to see the direct and indirect influence between variables, the study carried out decomposition of the influence between variables. Decomposition between variables involves the separation of total influence into direct and indirect influence. Direct influence refers to the influence of an independent variable on a dependent variable without the involvement of any intervening variables. In contrast, indirect influence signifies the effect of an independent variable on a dependent variable mediated by one or more intermediate variables. Based on the image of the estimation of structural model parameters, it can be explained that the direct influence and indirect influence among the variables of the research can be explained. Table 8 presents a brief summary of the causal relationship between study's latent variables, along with the corresponding t values as statistical tests.

Factors related to extension capacity

The influence of community leaders' role with participation

Hypothesis testing was conducted to examine the relationship between the role variables of community leaders (X8) and community participation in mangrove conservation (Y). The statistical analysis employed the Spearman Rank test, revealing a correlation coefficient (rs) value of 0.424. Kongkeaw *et al.,* (2019) reported that internal success factors, particularly leadership, play a key role in mangrove management.

The effect of government support with participation

This hypothesis analysis revealed a correlation between government support (X10) and community participation in mangrove conservation (Y). The variables of government support (X10) and community participation in mangrove conservation (Y) were carried out using the Spearman Rank test, yielding a correlation coefficient (rs) value of 0.366. The significance level obtained, at 0.004, is smaller than α (0.01). Consequently, the decision is made to accept H1, indicating that government support (X10) has a significant positive relationship with community participation in mangrove conservation (Y). The magnitude of this close relationship between government support (X10) and participatory community involvement in mangrove conservation (Y) is 36.6%. Government support is significantly related to participatory community involvement in mangrove conservation. The government plays an important role in establishing policies and regulations that support mangrove conservation. With a clear legal framework and support from the government, communities will be more encouraged to be involved in mangrove conservation because they see the government's commitment and responsibility to protect these ecosystems. The government is supported by Regulation No. 03/MENHUT-V/2004 (Minister of Forestry and Environment) for protecting mangroves. Damastuti and de Groot (2019) reported that government institutions have various efforts to protect mangrove areas, such as addressing tidal floods and erosion in Demak. The government plays a role in monitoring mangrove ecosystems. By involving communities in mangrove monitoring and management activities, the government can strengthen community participation in decision-making related to conservation. This fosters a sense of responsibility and shared ownership of the mangrove ecosystem, thereby encouraging more active participation.

The Influence of non-government organization role with participation

The Spearman Rank test was conducted to analyze the relationship between non-government organization variables (X11) and community participation in mangrove conservation (Y). The correlation coefficient (rs) value obtained was 0.268. The significance level, calculated at 0.038, is smaller than α (0.05). Therefore, the decision is to accept H1, indicating that non-government organizations (X11) are significantly related in a positive direction to community participation in mangrove conservation (Y). The magnitude of the relationship between non-government organizations (X11) and community participation in mangrove conservation (Y) is 26.8%. NGOs often play a leading role in organizing mangrove conservation activities. They form local working groups or initiatives that focus on mangrove conservation, coordinate field activities, and organize necessary resources and manpower. Good leadership and coordination from NGOs can enhance community participation in mangrove conservation. NGOs can provide training and assistance to communities in mangrove conservation techniques, resource management, and skills development related to environmental conservation. By increasing the capacity of communities, NGOs enable them to engage more effectively in mangrove conservation and take an active role in field activities. NGOs play a major role in decision-making in an area so that the community can express their aspirations (Abiddin *et al.,* 2022; Rahman and Tasnim, 2023). Social participation activities involve interacting with others in the community and must specifically involve others

(Levasseur *et al.,* 2010). To increase community participation, Figure 3 proposes an approach that emphasizes the role of leaders. These leaders should fulfill several key functions: supervising community activities, inviting new members, providing information and motivation, distributing rewards to engaged participants, and building trust within the community. Additionally, the government should offer its full support by providing funding, supervision, rewards, and preservation efforts. Furthermore, NGO involvement is crucial for offering thought leadership, management assistance, mentoring, and program planning). The SEM results indicate that increasing community participation relies on enhancing the role of leaders. Leaders should undertake tasks such as supervision, invitation, Einformation provision, motivation of the community, offering rewards to engaged community members, and fostering trust. Full support from the government, including funding, supervision, rewards, and preservation efforts, is crucial. Additionally, NGO involvement, encompassing thought contribution, management assistance, mentoring, and program planning, plays a significant role. Participation influences welfare; the more active the community, the more space there will be to utilize mangrove products and interact with other community members. This interaction enables the fulfillment of income, food needs, and the provision of adequate housing. The type of training that could be arranged for the community is Ecological Mangrove Rehabilitation (EMR), which has been implemented in South and North Sulawesi. EMR has been successfully implemented and well-documented for the past several decades in New World mangrove systems (Lewis, 2005) and was selected as a best practice for adaptation and trials in Indonesia. Mangroves can be restored or conserved through specific actions. First, for a given area of mangroves or former mangroves, it is essential to define the existing watershed and document any changes to the coastal plain hydrology that may have impacted the mangroves. Second, careful site selection must take place, considering the history of the site. This will likely involve an investigation of historical maps, aerial and satellite photography, and mapping of changes over time. Third, clearly stated objectives and achievable, measurable success criteria should be defined and incorporated into the proposed monitoring program. Fourth, restoration methodologies should acknowledge a history of routine failures in efforts to rehabilitate mangroves and propose the use of techniques that have proven successful. Fifth, once the initial restoration activities are complete, the proposed monitoring program should be initiated and used to determine whether the project achieved interim measurable success to indicate whether mid-course corrections are needed. Finally, results should be made available for others to learn from documented successes and failures. Village administrators can play a crucial role in protecting mangrove conservation through village laws, and their role must be strengthened as a national agenda. Through the promotion of ecotourism activities, mangrove rehabilitation can contribute to enhancing community welfare. Ecotourism activities aim to conserve the ecosystem while also preserving or improving the welfare of local people. The ecotourism and educational functions in mangrove forests can be developed, such as sightseeing the beauty of flora and fauna, as well as boating around the mangroves. In districts like Labuhan Maringgai and Pasir Sakti, training programs in mangrove tourism, forest honey cultivation, and crab farming are offered. These activities could serve as viable alternative livelihoods for local communities. The enhancement of community welfare can be achieved through the generation of increased incomes from these ecotourism and sustainable economic activities.

CONCLUSION

This study concludes that community participation in mangrove ecosystem rehabilitation in Labuhan Maringgai sub-district and Pasir Sakti sub-district is in the middle category level. It involves a low planning process, high implementation category, low participation in evaluation, and a high category in the utilization of results. Community involvement in mangrove rehabilitation can be increased with support from the government, community leaders, and NGO involvement. Additionally, the existence of farmer groups needs to be reviewed so that their presence can increase community participation. Communities actively involved in mangrove rehabilitation, both in implementation and result utilization, can improve community welfare, including income and access to clothing and shelter. The findings of this study indicate that community engagement in mangrove forest rehabilitation activities in Labuhan Maringgai District and Pasir Sakti District falls within the middle category. This suggests that there is still room for improvement in the level of participation, as the involvement of farmers in the middle category indicates a lack of public awareness regarding mangrove rehabilitation. Community participation, encompassing both the planning and evaluation of activity outcomes, remains in the low category. This could be attributed to the direct involvement of village administrators and officials in the development of mangrove rehabilitation strategies, with other members only being informed of decision outcomes. Similarly, the assessment of activities is conducted by village authorities and affiliated organizations. The level of engagement in mangrove rehabilitation initiatives, however, is in the high category. This is primarily because respondents were at the forefront of these endeavors, demonstrating their active participation in various activities such as planting, establishing nurseries, and advocating for mangrove conservation. The high level of participation in utilizing results is justified due to the community's direct and indirect exposure to the advantages provided by mangrove forests. Community participation in mangrove rehabilitation can be enhanced through the backing of governmental support, community leaders, and NGOs. However, to increase community engagement, an examination of the viability of farmer groups is necessary. Community welfare can be enhanced through the implementation and utilization of the results of mangrove rehabilitation, including income, access to clothing, and residence. The recommended strategy for mangrove conservation involves adopting an ecological systems approach. By employing this approach, coastal communities residing in mangrove forest areas gain a comprehensive perspective for studying environmental factors within mangrove ecosystems. The primary objective is to deepen understanding of organism development within these ecosystems. This approach views humans as integral components of the system, emphasizing a positive reciprocal relationship between humans and the environment. Various strategies for mangrove conservation planning incorporate Ecosystem Service Economic Valuation (ESEV). Ecosystem services, defined as the well-being provided by natural ecosystems to humans, necessitate a connection to human well-being and socio-economic values. This integration of human needs is coupled with environmentally friendly eco-farming practices, made accessible through boardwalks that promote ecotourism and public education. To enhance community participation in mangrove rehabilitation, the Participatory Rural Appraisal (PRA) method is employed. Implementation involves multiple communities facilitated by external entities such as NGOs and the Government. This approach adopts a "personal approach" by paying attention to and considering and addressing the specific needs of the community as the primary focus. Various mangrove conservation planning efforts include discussions and consultation activities. The community considers government support essential for mangrove rehabilitation, and communities understand the importance of mangrove forests. Community leaders have broad influence and authority in society, playing an active role in leading, guiding, and influencing community direction.

AUTHOR CONTRIBUTIONS

I. Listiana has designed research, collected data, conducted data analysis, interpreted data, and wrote the manuscript. D. Ariyanto has designed research, prepared the manuscript, wrote the manuscript, corrected the manuscript, and interpreted data.

All authors declare equal contributions.

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CONFLICT OF INTERES

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
α	Alpha
CO_2	Carbon dioxide
CBMM	community-based mangrove management
EMR	Ecological mangrove rehabilitation
ESEV	Ecosystem service economic valuation
km	Kilometer
LISREL	Linear structural relationships
M4CR	Mangrove for coastal resilience
MENHUT	Minister of Forestry and Environment
NGO	Non-governmental organization
PRA	Participatory rural appraisal
SEM	Structural equation modeling
SPSS	Statistical package for the social sciences

REFERENCES

Abdul-Rahaman, A.; Abdulai, A., (2020). Farmer groups, collective marketing and smallholder farm performance in rural Ghana. J. Agribusiness Dev. Emerg. Econ., 10(5): 511–527 (**17 pages**).

Abiddin, N. Z.: Ibrahim, I.; Aziz, S. A. A., (2022). Non-governmental organizations (NGOs) and Their part towards sustainable community development. Sustainability. 14(8): 1–13 (**13 pages**).

Antwi-Agyei, P.; Stringer, L.C., (2021). Improving the effectiveness of agricultural extension services in supporting farmers to adapt to climate change: Insights from northeastern Ghana. Clim. Risk Manage., 32: 100304 (**13 pages**).

Arifanti, V.B.; Sidik, F.; Mulyanto, B.; Susilowati, A.; Wahyuni, T.; Subarno.; Yulianti.; Yuniarti, N.; Aminah, A.; Suita, E.; Karlina, E.; Suharti, S.; Pratiwi.; Turjaman, M.; Hidayat, A.; Rachmat, H.; H., Imanuddin, R.; Yeny, I.; Darwiati, W.; Sari, N.; Hakim, S.S.; Slamet, W.Y.; Novita, N., (2022). Challenges and strategies for sustainable mangrove management in Indonesia: A Review. Forests. 13(5): 1–18 (**18 pages**).

Ariyanto, D.; Bengen, D.G.; Prartono, T.; Wardiatno, Y., (2020). Distribution and abundance of *Cerithideopsilla djadjariensis (*Martin 1899) (Potamididae) on *Avicennia marina* in Rembang, Central Java, Indonesia. Egypt. J. Aquat. Biol. Fish., 24(3):323–332 (**10 pages**).

Ariyanto, D.; Gunawan, H.; Puspitasari, D.; Ningsih, S.S.; Jayanegara, A.; Hamim., (2019a). Identification of the chemical profile of *Rhizophora mucronata* mangrove green leaves from the eastern coast of Asahan, North Sumatra, Indonesia. Plant Arch., 19(2): 4045–4049 (**5 pages**).

Ariyanto, D.; Gunawan, H.; Puspitasari, D.; Ningsih, S.S.; Jayanegara, A.; Hamim, H., (2019b). The differences of the elements content in *Rhizophora mucronata* leaves from asahan regency, north sumatra, Indonesia. Pol. J. Nat. Sci., 34(4): 481–491 (**12 pages**).

Ariyanto, D.; Bengen, D.G.; Prartono, T.; Wardiatno, Y., (2019c). The physicochemical factors and litter dynamics (*Rhizophora mucronata* Lam. and *Rhizophora stylsa* Griff) of replanted mangroves, Rembang, Central Java, Indonesia. Environ. Nat. Resour. J., 17(4): 11–19 (**9 pages**).

Ariyanto, D., (2019). Food preference on *Telescopium Telescopium* (Mollusca : Gastropoda) based on food sources in mangrove ecosystem. Plant Arch., 19(1): 913–916 **(4 pages).**

Ariyanto, D.; Bengen, D.G.; Prartono, T.; Wardiatno, Y., (2018a). Short Communication: The relationship between content of particular metabolites of fallen mangrove leaves and the rate at which the leaves decompose over time. Biodiversitas. 19(3):700–705 (**6 pages**).

Ariyanto, D.; Bengen, D.G.; Prartono, T.; Wardiatno, Y., (2018b). The association of *Cassidula nucleus (*Gmelin 1791) and *Cassidula angulifera* (Petit 1841) with mangrove in banggi coast, Central Java, Indonesia. AACL Bioflux., 11(2): 348–361 (**14 pages**).

Barbier, E.B.; Hacker, S.D.; Kennedy, C.; Koch, E.W.; Stier, A.C.; Silliman, B.R., (2011). The value of estuarine and coastal ecosystem services. Ecol. Monogr., 81(2): 169–193 (**25 pages**).

Bellaire, L. L.; Kenfield, M.; Janek, K.; Balch, W., Poulin, J.; Brown, L.; Mosiman, S.; Nichol, P., (2023). Do formal education or certification opportunities in sterile processing enhance career advancement? Perioper. Care Oper. Room Manage., 32: 100330 (**7 pages**).

Budiharta, S.; Meijaard, E.; Wells, J.A.; Abram, N.K.; Wilson, K.A., (2016). Enhancing feasibility: Incorporating a socio-ecological systems framework into restoration planning. Environ. Sci. Policy., 64: 83–92 (**10 pages**).

Chamberland-Fontaine, S.; Thomas Estrada, G.; Heckadon-Moreno, S.; Hickey, G.M., (2022). Enhancing the sustainable management of mangrove forests: The case of Punta Galeta, Panama. Trees, For. People., 8: 100274 (**12 pages**).

Damastuti, E.; van Wesenbeeck, B.K.; Leemans, R,; de Groot

R.S.;, Marcel J. Silvius, M.J., (2023). Effectiveness of community-based mangrove management for coastal protection: A case study from Central Java, Indonesia. Ocean. Coast. Manage. 238:106498 (**14 pages).**

Damastuti, E.; de Groot, R., (2019). Participatory ecosystem service mapping to enhance community-based mangrove rehabilitation and management in Demak, Indonesia. Reg. Environ. Change., 19: 65–78 **(14 pages).**

Damastuti, E.; Groot, R. De., (2017). Effectiveness of community-based mangrove management for sustainable resource use and livelihood support: A case study of four villages in Central Java , Indonesia. J. Environ. Manage., 203: 510–521 (**14 pages**).

Datta, D.; Chattopadhyay, R.N.; Guha, P., (2012). Community based mangrove management : A review on status and sustainability. J. Environ. Manage., 107: 84–95 **(12 pages).**

Djosetro, M.; Behagel, J.H., (2020). Building local support for a coastal protected area: collaborative governance in the bigi pan multiple use management area of Suriname. Mar. Policy., 112(15): 103746 (**10 pages**).

Ellison, A.M.; Felson, A.J.; Friess, D.A., (2020). Mangrove rehabilitation and restoration as experimental adaptive management. Front. Mar. Sci., 7: 1–19 (**19 pages**).

Evans, K.; Guariguata, M.R.; Brancalion, P.H.S., (2018). Participatory monitoring to connect local and global priorities for forest restoration. Conserv. Biol., 32(3): 525–534 (**10 pages**).

Fan, Y.; Chen, J.; Shirkey, G.; John, R.; Wu, S.R.; Park, H.; Shao, C., (2016). Applications of structural equation modeling (SEM) in ecological studies: an updated review. Ecol. Process., 5: 19 (**12 pages**).

Fielke, S.J.; Bardsley, D.K., (2014). The importance of farmer education in South Australia. Land Use Policy. 39:301–312 (**12 pages**).

Fischer, E.; Qaim, M. (2012). Linking smallholders to markets: determinants and impacts of farmer collective action in Kenya. World Dev., 40(6): 1255–1268 (**14 pages).**

Gayo, L., (2022). Local community perception on the State Governance of mangroves in Western Indian coast of Kinondoni and Bagamoyo, Tanzania. Glob. Ecol. Conserv., 39: e02287 (**11 pages**).

Guo, G.; Wen, Q.; Zhu, J., (2015). The impact of aging agricultural labor population on farmland output : from the perspective of farmer preferences. Math. Probl. Eng., 2015: 1–7 (**7 pages**).

Hartoko, A.; Chayaningrum, S.; Febrianti, D.A.; Ariyanto, D., Suryanti., (2015). Carbon biomass algorithms development for mangrove vegetation in Kemujan, Parang Island Karimunjawa National Park and Demak Coastal Area – Indonesia. Proc. Environ. Sci., 23: 39–47 (**9 pages**).

Inayat, W.; Jahanzeb Khan, M., (2021). A Study of job satisfaction and its effect on the performance of employees working in private sector organizations, Peshawar. Educ. Res. Int., 2021: 1751495 **(9 pages**).

Kongkeaw, C.; Kittitornkool, J.; Vandergeest, P.; Kittiwatanawong, K., (2019). Explaining success in community based mangrove management: Four coastal communities along the Andaman Sea, Thailand. Ocean Coast. Manage., 178: 104822 **(8 pages**).

Levasseur, M.: Richard, L.: Gauvin, L.; Raymond, É., (2010). Inventory and analysis of definitions of social participation found in the aging literature: Proposed taxonomy of social activities. Soc. Sci. Med., 71(12): 2141–2149 (**9 pages**).

Lewis III, RR., (2005). Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng., 24 (4): 403-418 (**16 pages**).

Listiana, I.; Sadono, D.; Tjitropranoto, P.; Ariyanto, D. (2019). Internet usage in agricultural extension activities in Lampung Province, Indonesia. Int. J. Innovative Technol. Exploring Eng., 8(12): 1486–1493 (8 pages).

Mbeche, R.; Ateka, J.; Herrmann, R.; Grote, U. (2021). Forest policy and economics understanding forest users ' participation in participatory forest management (PFM): Insights from Mt . Elgon forest ecosystem , Kenya. For. Policy. Econ., 129: 102507 (**12 pages**).

Ningsih, S.S.; Ariyanto, D.; Puspitasari, D.; Jayanegara, A.; Hamim, H.; Gunawan, H., (2020). The Amino acid contents in mangrove *Rhizophora mucronata* leaves in Asahan, North Sumatra, Indonesia. E3S Web of Conferences, 151, 1–3 (**3 pages**).

Nwankwo, C.; Tse, A.C.; Nwankwoala, H.O.; Giadom, F.D.; Acra, E.J., (2023). Below ground carbon stock and carbon sequestration potentials of mangrove sediments in Eastern Niger Delta, Nigeria: implication for climate change. Sci. Afr., 22: e01898. (**9 pages**).

Phiri, K.; Ndlovu, S.; Dube, T.; Nyathi, D.; Ncube, C.; Tshuma, N., (2020). Access to formal education for the San community in Tsholotsho, Zimbabwe: challenges and prospects. Heliyon., 6(7): e04470 (**8 pages**).

Pringgenies, D.; Setyati, W.A.; Djunaedi, A.; Pramesti, R.; Rudiyanti, S.; Ariyanto, D., (2021). Exploration of antimicrobial potency of mangrove symbiont against multi-drug resistant bacteria. J. Ilm. Perikan. Kelaut (Sci. J. Fish. Mar.)., 12(2): 222–232 (**11 pages**).

Pringgenies, D., Wilis, A.S.; Feliatra, F.; Ariyanto, D. (2023). The antibacterial and antifungal potential of marine natural ingredients from the symbiont bacteria of mangrove. Glob. J. Environ. Sci. Manage., 9(4): 819–832 (**14 pages**).

Rahman, S.; Tasnim, F., (2023). The role of NGOs in ensuring local governance in Bangladesh: from the perception of other actors of governance. Asia-Pac. J. Reg. Sci., 7: 1007–1034 (**28 pages**).

Ramlall, I., (2016). Definition of SEM, Applied Structural Equation Modelling for Researchers and Practitioners, Emerald Group Publishing Limited, Leeds. 1-12 (**12 Pages**).

Sadono, R.; Soeprijadi, D.; Susanti, A.; Matatula, J. Pujiono, E. Idris, F.; Wirabuana, P.Y.A.P., (2020). Local indigenous strategy to rehabilitate and conserve mangrove ecosystem in the southeastern gulf of kupang, east nusa tenggara, Indonesia. Biodiversitas. 21(3): 1250–1257. (**8 pages**).

Sam, K.; Zabbey, N.; Deebari, N.;Chinwendu, J.; Mirian, C., (2023). Towards a framework for mangrove restoration and conservation in Nigeria. Reg. Stud. Mar. Sci., 66:103154 (**12 pages**).

Setiyaningrum, I.F., (2019). Community perceptions on mangrove forest sustainability in Dukuh Bendo, Jatikontal Village, Purwodadi District, Purworejo Regency, Central Java. IOP Conf. Ser: Earth Environ. Sci., 271(1): 1–10 (**10 pages**).

Singh, S.G.; Vennila, A.; Singh, R.; Bharti, V.S.; Shukla, S.P.; Purushothaman, C.S., (2023). Standing carbon stock of Thane Creek mangrove ecosystem: An integrated approach using allometry and remote sensing techniques. Reg. Stud. Mar. Sci., 67: 103207 (**11 pages**).

Spalding, M.; Parrett, C.L., (2019). Global patterns in mangrove recreation and tourism. Mar. Policy. 110:103540 (**8 pages**).

Stein, C.M.; Morris, N.J.; Nock, N.L., (2011). Structural Equation

Modeling. Method. Hum. Gen., 495–512 (**18 pages**).

Taher, T.B.; Althaus, C.E.; Paul J. Tranter, P.J.; Megan C. Evans, M.C, (2023). Impacts of shrimp aquaculture on the local communities and conservation of the world's largest protected mangrove forest. Environ. Sci. Policy. 147: 351-360 (**10 pages**).

Takrina, N.D.; Chuan, O.M.; Pin, T.G.; Femnisya, I.; Fathinah, A.; Ramadhan, A.N.B.; Hermawan, R.; Adiwibowo, A., (2023). Land us e variation impacts on trace elements in the tissues and health risks of a commercial fish. Global J. Environ. Sci. Manage., 9(3): 445-462 (**18 pages**).

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REVIEW PAPER

A bibliometric study on organization citizenship behavior for the environment

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ABSTRACT

Organization Citizenship Behavior for the Environment is discretionary and proactive behavior that contributes to more effective environmental management by organizations. It originates from the organizational behavior concepts of organizational citizenship behavior and discretionary pro-environmental behaviors. As environmental challenges have become more complex, they cannot be managed solely through formal procedures. Thus, there is a need for Organization Citizenship Behavior for Environment. It does not prescribe the pro-environmental behaviors employees are expected to engage in. Organization citizenship behaviour for the environment includes various workplace environment management initiatives, such as sharing knowledge that can prevent pollution, providing solutions for waste reduction, and implementing environmentally friendly technologies. This study aimed to synthesize the literature on Organization Citizenship Behaviour for the environment through a bibliometric analysis. Bibliometrics is a methodology that analyzes academic research and addresses massive volumes of information. It is a big data analytics technique used in systematic literature reviews and entails quantitatively analyzing scholarly works. It examines research trends, productivity, and scientifically linked patterns in-depth. Journal publications from 2000 were downloaded from the Scopus repository in comma-separated values and plain-text formats. The VOSviewer program was used to visualize and analyze various trends and patterns in the available literature. The results show that the literature on Organization Citizenship Behavior for the environment is increasing rapidly, as are the citations of the topic. Over the past decade, 187 articles have been published on this topic. In the same period, the term organization citizenship behavior for the environment was found to be a keyword used 54 times. This trend is expected to continue. This study contributes to an improved understanding of the emerging concept of organization citizenship behaviour in the environment. This study presented a macroscopic summary of the main characteristics of organization citizenship behaviour in the environment, which was not attempted earlier. This study also discusses the limitations and scope for future research. These limitations include limiting the study to the Scopus database and methodology used. For instance, the bibliometric method is sensitive to the selection criteria and filters used to construct a sample. It is possible that the selection criteria concealed certain relevant articles based on the search query used in the study.

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INTRODUCTION

Over the last few decades, environmental and ecological concerns have attracted academic interest in "corporate greening" because it is an essential organizational issue (McKinsey and Company, 2011; Samimi and Moghadam, 2024). Moreover, environmental issues are increasingly moralized in the public sphere, pressuring businesses to advance the environmental cause more responsively and comprehensively (Ortiz-Avram et al., 2023; Pandey *et al.,* 2013). Reflecting this trend, the concept of corporate greening emphasizes the need to treat the natural environment as an essential stakeholder (Driscoll and Starik, 2004; Hamsal *et al*., 2023) and to leverage employees' civic attitudes and citizenship behaviors (Daily *et al.,* 2008). This thought process explores how individual and organizational characteristics influence employees' discretionary and proactive involvement in environmental impact management (Sulphey and Safeer, 2017; Matheen *et al*., 2023; Temminck *et al.,* 2015). This proactive behavior improves corporate environmental performance and plugs environmental gaps beyond formal organizational structures (Raineri and Paille, 2016). Employees' environmental actions are critical elements of corporate greening (Bauer and Aiman-Smith, 1996; Ramus and Killmer, 2007; Daily *et al.,* 2008). Globally, academics and environmental policymakers firmly believe that environmental damage, such as resource depletion (Moghadam and Samimi, 2022), increasing pollution (Samimi and Shahriari-Moghadam, 2023), and biodiversity loss (Samimi *et al.,* 2023), occurs due to industrial actions and human behavior (Khan *et al.,* 2020; Urban *et al*., 2023; Samimi and Nouri, 2023). In response to this global problem, organizations must pay greater attention to adopting green behavior for employees because people are a critical component of organizations (Daily *et al*., 2008; Shafaei and Nejati, 2023). As a solution, Organization Citizenship Behavior for the Environment (OCB-E) originated. Borial (2008) defined it as "individual and discretionary social behaviors that are not explicitly recognized by the formal reward system and that contribute to a more effective environmental management by organizations." This recent concept originates from Organizational Citizenship Behavior (OCB) and discretionary pro-environmental behaviors (Daily *et al.,* 2008; Borial, 2008; Yuriev *et al.,* 2018). Self-efficacy, morals and values, self-identity, and individual environmental beliefs stimulate OCB-E (Ciocirlan, 2017; Huda et al., 2021; Van der Werff *et al.,* 2013). This does not involve any prescribed pro-environmental behaviors employees must engage in (Robertson and Barling, 2017). Alternatively, it proposes various initiatives in the workplace, such as sharing knowledge that can prevent pollution, providing solutions for waste reduction, and implementing environmentally friendly technologies (Boiral and Paille, 2012; Liu *et al*., 2020). Since the concept of OCB-E was first suggested in the early part of the century (Boiral, 2009; Dialy *et al.*, 2008), it has attracted the interest of many academics (Paillé *et al*., 2017; Raineri and Paillé, 2016). Despite its recent origin, OCB-E has received wide attention, and there is a sizeable body of literature on it (Lamm *et al*., 2013; Paillé *et al.,* 2013; Raineri and Paillé, 2016). OCB-E is important because of the complexity of environmental challenges that cannot be controlled solely through formal procedures. Furthermore, OCB-E is relevant because of the complexity of environmental challenges that cannot be managed solely through formal procedures (Liu and Qi, 2022). OCB-E, a discretionary initiative of employees, helps enhance energy efficiency, adopt appropriate waste management techniques, encourage robust green initiatives, and positively impact environmental performance (Boiral and Paille, 2012; Ramus, 2001; Ramus and Steger, 2000). Employees with OCB-E also have higher levels of voluntary eco-initiatives and heightened environmental awareness (Huda *et al.,* 2021; Paillé *et al.,* 2013; Raineri and Paillé, 2016). Employees demonstrating OCB-E also propose energy and resource reduction and urge colleagues to conduct environmentally friendly organizational tasks (Boiral and Paille, 2012; Neessen *et al.,* 2021). OCB-E fosters complementarity with formal environmental management systems (EMS) to address environmental gaps unidentified by regulatory systems. It also directly assists organizations in lowering environmental costs and improving their environmental reputation (Alt and Spitzeck, 2016; Zhao and Zhou, 2020). The importance of OCB-E in fostering voluntary environmental behavior highlights its importance in changing industrial scenarios. This study intends to examine the work done in OCB-E to assess its current position and importance through a bibliometric analysis. Bibliometric methods quantitatively analyze published materials (Ellegaard and Wallin, 2015; Tu *et al.,* 2021). It provides a consistent and uniform collection of indicators (Van Raan, 2003). It also examines an article's effect on future research by tracking the citations of a published article. This is because being referenced implies that the original researcher has an influence (Cooper, 2015). It examined publication patterns using quantitative analyses and statistics. Examining the current knowledge on OCB-E enables one to comprehend the themes and major theoretical approaches and identify gaps and crucial opportunities for future growth. Bibliometric studies are scarce on OCB-E. This bibliometric review aims to fill this research gap by objectively assessing this area. This study aimed to close this gap through quantitative and visual bibliometric analyses. This study aimed to contribute to the literature on corporate greening and organizational behavior (OB) by synthesizing the available literature on OCB-E. This objective was achieved through a bibliometric analysis. Globally, investigators have used bibliometric analyses to study specific trends across multiple disciplines (Falagas *et al.,* 2006; Sulphey, 2022; Wang *et al*., 2009). Specifically, the method helps assess and quantify research patterns. It also helps to identify scientific outputs based on authors, keywords, journals, citations, research productivity, and many other parameters (Abramo *et al.,* 2011; Wang *et al*., 2009). Studies that have examined individual differences as predictor variables of socially and environmentally conscious work behavior, environment-specific values, anxieties, perceptions, and belief systems have received more attention than those that have examined general traits linked to a broader range of other work outcomes (Aguinis and Glavas, 2012). Four variables influence individual environmental behavior: contextual, attitudinal, sociodemographic, and habitual. Awareness of environmental issues and a sense of duty have positively impacted an individual's environmental behavior (Boiral *et al*., 2013; Erdogan *et al*., 2015; Kalamas *et al*., 2014). Values also influence people's awareness of environmental issues and their negative consequences. The perceived ability to decrease impact shapes one's sense of obligation to act on such consequences. The stronger one's environmental awareness, the higher one's altruistic, prosocial, and biospheric values and the resultant pro-environmental activities (Boiral, 2009). There are many socially and environmentally conscious work behaviors, among which OCB-E is of prime importance. Identifying generic personalities and specific moral traits that may stimulate underlying motives also helps to identify a theoretical route for inducing green employee behavior, such as OCB-E, and its application in organizations. OCB-E is individual, informal, voluntary, and flexible behavior that promotes and facilitates organizational greening. Daily *et al.* (2008) define OCB-E as the "discretionary acts by employees within the organization not rewarded or required that are directed toward environmental improvement." The OCB-E is a modified version of OCB. The main difference between the two is that, while in OCB, employees engage in proactive behaviors with the organization's best interests in mind, OCB-E involves concern and voluntary behaviors that benefit the environment (Boiral *et al.,* 2015; Paille and Boiral, 2013). Some social scientists (for instance, Boiral, 2009; D'Arco & Marino, 2022; Paillé *et al.,* 2014) have identified OCB-E as an environmental citizenship behavior (ECB). Boiral (2009) identified ECB as "innovative and spontaneous employee acts directed toward environmental improvement in the work context." OCB-E is the most commonly used terminology. OCB-E is characterized by discretionary and voluntary behavior (Boiral & Paillé, 2012; Tosti-Kharas *et al.,* 2016) and does not form part of any formal job description (Lamm *et al.,* 2013; De Groot & Steg, 2008; Kim *et al*., 2015). OCB-E has its moorings in citizenship theory. This theory implies that social and environmental responsibility is a thinking style or mode of citizenship exercised in individual lives and daily routines. According to this theory, citizenship expects individuals and organizations to act in ways that preserve the integrity of nature and increase social justice, even if there are no returns or rewards for accomplishing it. OCB-E is not limited to social-environmental theory (Norton *et al.,* 2015; Stern, 2000). OCB-E is a moral-political orientation that adopts ecologically sustainable conduct in private, organizational, and public arenas by defining the link between individuals and the "common good" (Sarid and Goldman, 2021). Individuals' ecological and environmental values may motivate them to act responsibly if they believe they can make a difference to benefit the environment (Ciocirlan, 2017; Lamm *et al.,* 2015; Osbaldiston and

Table 1: Types of Organization citizenship behavior for the environment (Boiral and Paillé, 2011)

No.	Type	Description
1	Eco-initiative	This involves various employee-led pro-environmental activities in the workplace, like recycling, reducing the consumption of finite resources, making pro-environmental suggestions, and voluntary initiatives to reduce greenhouse gas emissions.
2	Eco-civic engagement	This relates to contributions to the organization's environmental activities, such as participation in environmental events, promoting the organization's green image, and voluntary participation in the organization's environmental events.
3	Eco-helping	This type concerns assisting colleagues with environmental concerns, expressing opinions on environmental issues, and adopting more ecologically responsible behavior.

Schott, 2012). Adequate empirical evidence has been accumulated on various aspects of OCB-E (Ren *et al.,* 2020; Ruiz-Palomino and Martínez-Cañas, 2014). Empirical evidence suggests that environmental beliefs are precursors of OCB-E (Bissing-Olson *et al.,* 2013; Lamm *et al.,* 2013; Temminck *et al.,* 2015). For instance, Priadi *et al.* (2018) found that variables such as environmental sensitivity, knowledge of ecology, and locus of control positively affect OCB-E. Paillé *et al.* (2014) believe that OCB-E tends to have a multiplier effect on environmental performance. Boiral and Paillé (2012) identify three types of OCB-E, as detailed in Table 1.

Each type presented in the Table focuses on different aspects of environmental management. For example, while eco-initiative involves all personal environmental initiatives, eco-civic engagement identifies contributions to various corporate environmental activities, and eco-helping is mutual pro-environmental assistance towards colleagues (Hanna et al., 2000; Ramus and Steger, 2000; Ramus, 2001). This typology has been confirmed by Liu et al.(2017). OCB-E helps employees perform actions beyond their routine jobs to enhance their green targets, improve organizational environmental performance, and contribute successfully to the environment (Adjei-Bamfo *et al.,* 2020; Alt and Spitzeck, 2016; Kalimmullah *et al.,* 2019; Paille *et al.,* 2013). Factors positively affecting OCB-E include administrative supervision (Paille *et al.,* 2017) and a pro-environmental atmosphere (De Groot and Steg, 2008; Zientara and Zamojska, 2018). It also significantly enhances environmental performance (Boiral, 2009; Ramus and Killmer, 2007; Steg *et al.,* 2014). Studies have also confirmed the role of OCB-E in improving the organizational pro-environmental atmosphere (Paille *et al.,* 2017; Zientara and Zamojska, 2018). Furthermore, if OCB-E exists in an organization, it becomes easy to implement environmental management practices and fill gaps in environmental practices outside all formal systems (Lülfs and Hahn, 2013; Raineri and Paille, 2016). Recent research on OCB-E has indicated the benign role of HRM towards environmental management processes using an employee-centric approach (Khalid *et al.,* 2022). Furthermore, the benefits of OCB-E have been well-documented in the literature (Ren *et al.,* 2020; Paillé and Meija-Morelos, 2019). Primarily, OCB-E enhances workplace-specific positive environmental behaviors. It helps organizations improve their environmental performance (Herlina *et al.,* 2023; Hameed *et al.,* 2020; Khalid *et al.,* 2022; Sulphey, 2017) and is essential to inculcate and nurture OCB-E among the younger generation, as such an effort will help them account for their actions towards the environment and build a promising future. The apparent benefits and relevance of OCB-E have encouraged the European Union (EU) and United States (US) governments to enact regulations encouraging it within companies (Herlina *et al.,* 2023). All these factors present the importance of OCB-E in the current situation, wherein the environment is under constant threat. Furthermore, it could benefit organizational performance and the potential for long-term reputation. This study aimed to synthesize the available literature on OCB-Es. The present study is expected to help the study of environmental management and OCB-E, as it highlights the growing importance of the concept and its current position. This study aimed to examine the work done in OCB-E to assess its current position and importance through a bibliometric analysis. This study used journal publications from the year 2000 downloaded from the Scopus repository. A software tool for constructing and visualizing bibliometric networks (VOSviewer) was used to visualize and analyze the various trends and patterns in the available literature. This study aimed to examine the work done in OCB-E to assess its current position, publication productivity, and importance through a bibliometric analysis. This study conducted an in-depth examination of research trends, productivity, and scientific link patterns. Journal publications published since 2000 in Scopus were used in this study.

METHODOLOGY

The term "bibliometrics" was first used by Paul Otlet in 1934 (Rousseau, 2014; Syafrudin *et al.,* 2023). This was later developed by Broadus (1987), who defined it as "the quantitative study of physical published units, or bibliographic units, or the surrogates for either." Bibliometrics analyzes academic research and deals with vast volumes of information (Makarius *et al.,* 2020; Mustak *et al*., 2021). It is a big data analytics technique used in systematic literature reviews and entails quantitatively analyzing scholarly works (Broadus, 1987). It enables examining scientific activities from several perspectives (Dickersin *et al.*, 1994; Gaur and Kumar, 2018). It also helps collect and classify complex bibliometric data. Bibliometric study citation and cocitation analyses help delve into the trends and characteristics of published (Broadus, 1987). The analysis helps uncover emerging trends such as publication, collaboration patterns, and research constituents. It also uses a qualitative methodology to investigate the intellectual structure of specific domains in the existing literature. This study focused on the content of the OCB-E. The content analysis used was an investigative system that aimed to analyze and systematize data in a way that could be replicated. Considering and deciding on the documents to be analyzed is of utmost importance. The methodology has the following different stages:

The time frame for selecting articles

Articles on OCB-E published in the last 20 years (from 2000) in the Scopus repository were considered for this study. This has facilitated the authors' recent publication on this topic. Elsevier's Scopus database is a well-known and complete social sciences database. It is the world's largest abstract and citation database, with the widest coverage of peer-reviewed literature on various subjects (Pham-Duc *et al*., 2022). Scopus also has an extensive quality assurance process that constantly monitors and improves all data elements (Basss *et al.*, 2020). This study did not use multiple databases other than Scopus simultaneously, as it would help reduce potential errors due to duplications. Furthermore, the use of a single database is adequate for scientific examination. Scopus was identified as the data source, as it is the major repository of multidisciplinary peer-reviewed articles and is widely used in similar studies (Eito-Brun, 2018; Pham-Duc *et al*., 2022; Sulphey, 2019; 2022). Many studies have used the Scopus database to conduct bibliometric reviews (Faisal, 2023; Pham-Duc *et al*., 2022). Scopus enabled the authors to publish recent publications on OCB-E.

Data mining and extraction

Publications indexed in the Scopus database were extracted. The Scopus database was mined for the articles included in this study. As Scopus is a comprehensive source, it was chosen to gather literature on a given topic. Since the concept of OCB-E is recent, bibliometric analysis has been utilized in publications since 2000. Journal publications published in 2000 were downloaded in comma-separated values (CSV) and plain text formats. No publications were found before 2000. Other aspects, such as keywords, citations, and bibliographic information, were also downloaded. A total of 862 publications were retrieved from the Scopus database and analyzed to provide representative and informative perspectives on the topic. Keywords like "*Organization citizenship behavior for the environment, OCB-E"* were used to identify the required publications. Although the authors attempted to include all possible articles, they did not claim completeness or exhaustiveness.

Selection of articles

Data mining helped to generate multiple potential publications. Every effort was made to minimize selection bias. All efforts were made to eliminate replication, reduce disparities across the selected studies, and boost data quality. Finally, irrelevant publications were excluded, for which a clear criterion set by Dickersin *et al.* (1994) for selecting the studies was followed. A few publications were excluded because they were not appropriate for the analysis. All duplicate and irrelevant articles were excluded to maintain uniformity and eliminate prejudice.

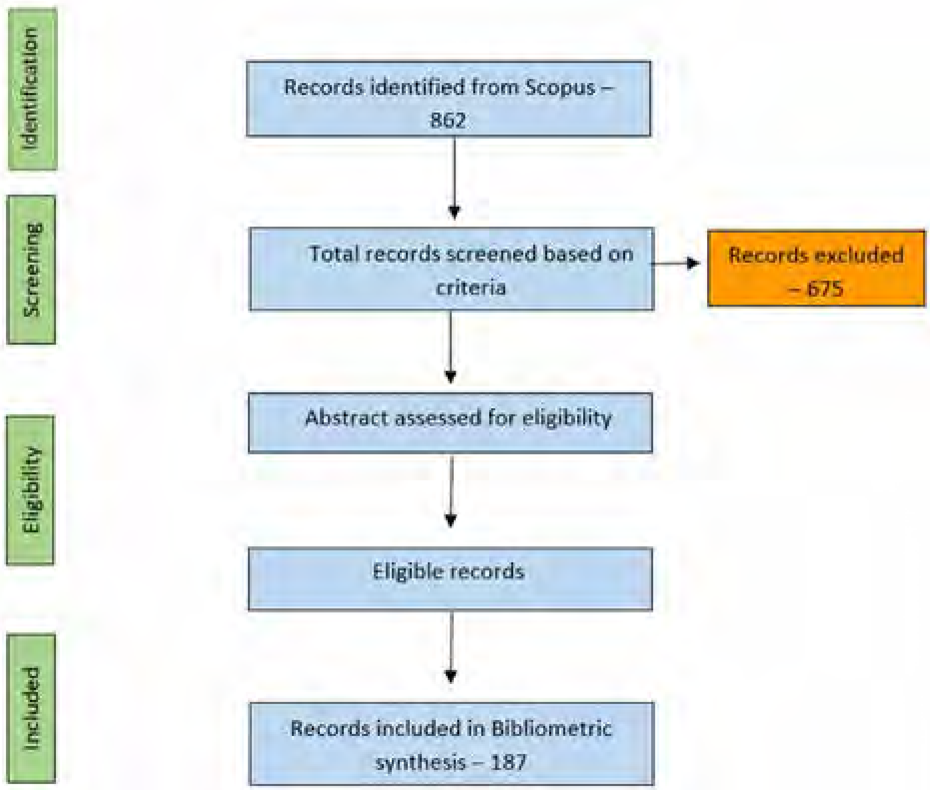

Fig. 1: The study flow diagram

Bibliometric analysis of extracted publications

A systematic review guided by a set of inclusion and exclusion criteria was applied to filter articles unrelated to the objectives and scope of the bibliometric search. A systematic review procedure was adopted to ensure transparency in the bibliometric analysis by focusing on OCB-E (Gora, 2019). This study uses VOSviewer as an analytical tool to visualize and analyze various trends and patterns in the literature. VOSviewer is simple and can be used to explore numerous data relationships. Furthermore, it is an open-source program that produces better results from medium and large datasets by performing mapping analyses (Moral-Munoz et al., 2019). This software supports bibliometric analysis by producing co-authorship, co-citation, and co-occurrence maps. It is an essential tool in this study because it offers additional features such as searching, magnification, and navigating (Van Eck *et al.,* 2010). VOSviewer also displays the overall research trend and general and cooperative network analysis while integrating network visualization and automatic cluster labeling to examine the possible knowledge structure in the literature for further investigation. The software aids bibliometric analysis by generating co-occurrence maps, co-authorship, and co-citation. The software also has other features, such as searching, magnification, and navigation, making it a crucial tool in this study (Van Eck *et al.,* 2010).

Classification of articles

The publications were shortlisted, and keywords like "organization citizenship behavior for the environment, OCB-E, Environmental Management, environmental performance" were identified. Based on the sorting list, a bibliographical list of 187 publications was prepared for classification. All these publications had the identified keywords, originality of the articles, aims of the study, and relevance. Our analysis was based on 187 publications. These results are presented in the following sections. The flow diagram is shown in Fig. 1.

Table 2: Number of articles with OCB-E

Year	Number of publications	Percent (%)
2022	32	17.1
2021	37	19.8
2020	25	13.4
2019	23	12.3
2018	17	9.1
2017	7	3.7
2016	9	4.8
2015	7	3.7
2014	5	2.7
2013	5	2.7
2012	4	2.1
2011	2	1.1
2010	2	1.1
2009	7	3.7
2008	1	0.5
2007	1	0.5
2002	1	0.5
2000	2	1.1
Total	187	100

Initially, a descriptive analysis was performed on the data, which analyzed the basic information of the 187 retained articles, including the number of publications by year and journals linked to the research. This was followed by cocitation analysis using VOSviewer software, which generated cocitation clusters. The clusters were then labeled to visualize the scientific structure of the study topic. Subsequently, co-keyword analysis chronologically classified the studies based on their publication dates. This facilitated an unambiguous description of the developments in this research topic. This study identified several publications on OCB-E from the Scopus database that were shortlisted from indexed international journals, including subscribed and open-access journals. These results are presented in the following sections. First, we performed a citation analysis, a scientific mapping, because citations form significance, relevance, and rational associations between publications. This analysis presents the reputation of a research work or author. Citation analysis examines the impact of the number of citations a publication receives. This analysis is an effective and unbiased measure of impact. Furthermore, a citation analysis offers an understanding of the rational dynamics of OCB-E. Citation analysis is presented in the following sections. From the analysis, it is found that 187 publications were found to have OCB-E in the title or as a keyword. Of the extracted publications, 169 were empirical: seven conference articles, six book chapters, and five reviews. The details of the extracted articles based on the year of publication are presented in Table 2. The study did not identify any articles published before 2000, indicating that the term OCB-E originated only at the turn of the century. Furthermore, there has been a steady increase in the number of publications on OCB-E. It is heartening to note that there was (especially post-2017) a quantum leap in publications. As of September 2022, when the authors extracted the publications, 32 articles had been identified, indicating the 'concept's popularity among social scientists. This concept is expected to soon gain popularity with multiple publications in the area.

A few authors authored multiple articles, the top of which were Boiral and Paillé, with 12 and 10 articles, respectively. Details of the authors with the maximum number of publications are presented in Table 3.

Multiple publications have used OCB-E and related topics as keywords. Details are presented in Table 4. It can be observed that OCB-E occurred 54 times in the keywords of the extracted publications. Other keywords included environmental management, organizational citizenship, leadership, and organizational citizenship behavior.

White and Griffith (1981) introduced the author cocitation analysis (ACA), which has been applied in bibliometric research. ACA measures the number of

Table 3: Authors with a maximum number of publications

Author details	Number of publications
Boiral, O.	12
Paillé, P.	10
Khan, N.U.	5
Wang, M.	4
Channa, N.A.	3
[illegible]	[illegible]

Table 4: Occurrences of keywords

Keywords	Occurrences
organizational citizenship behavior for the environment	54
Environmental management	29
Organizational citizenship	28
Corporate social responsibility	19
Organizational citizenship behaviors	19
Sustainability	19
Environmental performance	16

Table 5: Top cited authors and journals

Author details	No. of citations	Publication
Paillé et al., 2013	372	International Journal Of Human Resource Management
Boiral and Paillé, 2011	270	Journal of Business Ethics
Kim et al., 2014	241	Journal of Management
Daily et al., 2008	238	Business and Society
Boiral, 2008	234	Journal of Business Ethics
Rupp and Mallory, 2015	228	Annual Review Of Organizational Psychology And Organizational Behavior
Miles et al., 2002	185	International Journal Of Selection And Assessment
Raineri and Paille, 2016	155	Journal Of Business Ethics

references to a publication and another 'author's work (Jeong *et al*., 2014). The ACA network is illustrated in Fig. 2. Table 5 lists the most cited authors. The table shows that Paillé *et al*. (2013) was the most cited publication, with 372 publications. This was followed by Boiral and Paillé (2011), with 270 publications, and Kim *et al.* (2014), with 241 citations.

It is worth noting from Table 5 that most publications were in reputed journals with very high citations. Three articles were published in the Journal of Business Ethics.

The concept of OCB-E, which originated a decade ago, has attracted widespread research interest (Boiral *et al.,* 2013; Paillé *et al.,* 2013; Sulphey *et al.,* 2023). It must be noted that the concept was new and originated only at the turn of the century (Boiral, 2008; Daily *et al.,* 2008). Deep interest in the topic will continue to rise as discretionary and proactive behaviors such as OCB-E in environmental impact management are now indispensable for any organization (Borial, 2008; Huda et al., 2021; Liu *et al.,* 2020). OCB-E is closely associated with the broad disciplines of environmental management and organizational behavior. It is also related to topics such as pro-environmental and green behavior. Research on OCB-E could positively contribute to all these disciplines and topics substantially and help enrich the literature. This study employs a bibliometric approach that provides a more in-depth examination of research trends, productivity, and scientific link patterns (Cucari *et al*., 2022; Donthu *et al*., 2021*).* This methodology is objective, systematic, transparent, and ideal for identifying unique and associated networks and providing domain summaries. A well-conducted bibliometric study can significantly improve the field by enabling a comprehensive view by detecting research gaps and critically analyzing contextualized research issues (Broadus, 1987; Dickersin *et al.*, 1994;

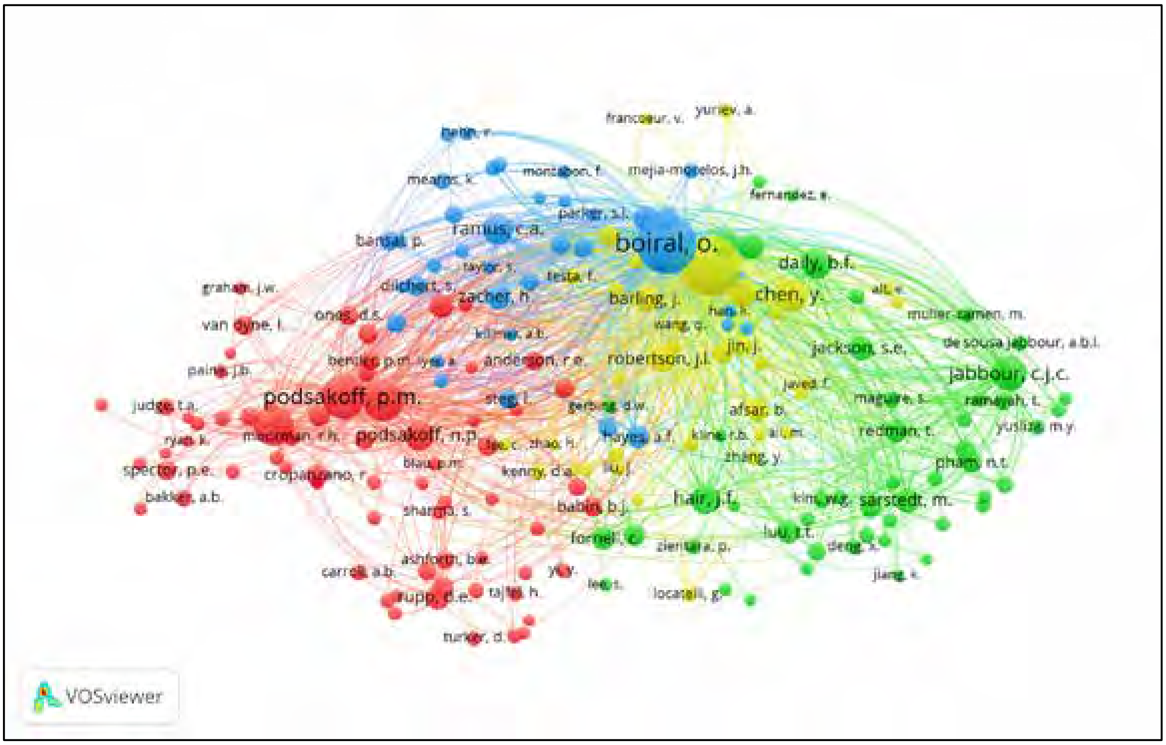

Fig. 2: Author cocitation network

Donthu *et al.*, 2021). The study investigated and obtained information on major areas of OCB-E, such as influential authors, keywords, publications, and citations. It also engages in network analysis to extract relationships between topics and identify themes and subthemes in OCB-E literature. It is a distinct, voluntary, and discretionary social behavior not overtly recognized by formal management systems (Boiral, 2008; Boiral *et al.,* 2013; Paillé *et al.,* 2013). It can contribute to productivity, reduce costs, improve employee engagement, and enhance retention (Sarid and Goldman, 2021). One of humanity's most critical challenges is the long-term ecological impact of environmental degradation. Excessive human interference, inability to practice sustainable development, ineptness of enforcement authorities, and poor community reactions to environmentally conscious ways of life are all causes of environmental calamities. They can damage ecosystems and cause habitat destruction, human health challenges, and species extinction. Institutional rules, programs, and environmental management systems seldom succeed in regulating organizational responses to environmental issues and concerns. Individual pro-environmental discretionary behaviors not explicitly recognized by the formal system deliver only sustained environmental performance (Miles *et al.*, 2002). Ecological awareness and identity must be nurtured to conserve an increasingly threatened environment. Several factors contribute to attitudes and behaviors that facilitate environmental performance. Some of these include personal environmental beliefs (Paillé *et al.*, 2020), green values (Hooi *et al.,* 3021; Sulphey *et al.,* 2023), and personality (Terrier *et al.,* 2016). Traditionally, individual characteristics have received scant attention from organizational scientists concerned with ethical ramifications and environmental sustainability. This study identifies a reversal of this trend after the turn of the century. The present work examined the research interests in OCB-E among social and organizational scientists. OCB-E, which is relatively new, has its edifice in business and management, with firm roots in environmental science literature. OCB-E embodies multifaceted behavior-based workplace pro-environmental behaviors, such as recycling and conservation, enacted by organizational members without external influence. Such behaviors can influence organizations to improve their environmental performance by promoting initiatives among colleagues and encouraging them to engage in pro-environmental behaviors. OCB-E is a voluntary action by employees who are not rewarded and is aimed at improving the environment. Previous research has shown that high levels of OCB-E are a significant factor in environmental conservation (Boiral, 2008; Boiral and Paillé, 2011; Paillé, 2019). Furthermore, environmental transformational leadership, particularly immediate leaders, is vital for producing sparks toward and enhancing discretionary behavior. Research evidence also suggests a positive relationship between OCB-E and employees' moral reflectiveness and ethical ramifications of environmental deterioration at work. This directly affects morally laudable and environmentally friendly work practices but is not formally encouraged. By shedding light on the impact of moral reflectiveness and voluntary behaviors, such as OCB-E, the current research helps advance the understanding of environmental sustainability in organizations. Furthermore, Kim *et al.* (2014) found that moral reflectiveness is a proximal driver of voluntary green behavior at work. This study quantitatively summarizes the pioneering efforts in OCB-E. It also succeeded in identifying the research prospects and fields of OCB-E. Towards this, this study provides bibliometric evidence from published research. This study is one of the few to present a bibliometric analysis of OCB-E using the Scopus database. This study analyzes various categories in the literature, including the most influential authors, keywords, and themes. This study also presents a rigorous background for OCB-E research, as it synthesizes and reviews the content of recent research. This analysis provides an objective reflection of the available literature on OCB-E. This review covers more than a decade and identifies productive authors and publications. Co-occurrence analysis of keywords and network visualization aided in determining the knowledge structure of OCB-E. This study extracted three main segments: research area, context, and research methods. This will facilitate the identification of research gaps that can provide future research directions. This study provides direction and knowledge on the previous, present, and future outcomes of OCB-E to construct conceptual and theoretical paradigms. This study also demonstrates that OCB-E research is relatively new and important to industry and academia. These findings have also contributed to an improved understanding of the emerging concept of OCB-E. Regarding the multiple foci of OCB and its determinants (Liu *et al.*, 2022; Chiaburu *et al.,* 2011), scant literature exists on the processes that give rise to specific behaviors, such as OCB-E. Therefore, additional empirical studies are required in this regard.

Managerial implications

Organizations are under pressure to perform better in terms of their environment. Unfortunately, green and non-green companies are not usually graded and named in business media. Owing to demands from multiple stakeholders, financial institutions worldwide have started creating various green indices. Stakeholders now signal their intense desire for a more environmentally friendly work atmosphere, products, and services. Understanding individual predispositions such as OCB-E provides valuable guidance for aligning work-related behaviors with stakeholders' demand for green products. Hiring those with high levels of OCB-E would go a long way for any firm to address environmental concerns by relying on workers who are likely to engage in voluntary activities through moral reflectiveness, thus boosting the organization's environmental performance. The OCB-E is paramount in the current industrial scenario because of the diversity and multiplicity of environmental issues and the inherent limitations of formal EMS. OCB-E also helps establish mutual relationships and collaboration among organizational members toward involvement in environmental protection and pollution prevention measures, as current environmental problems are complex and cannot be solved merely through formal systems (Boiral, 2008). The complexity of current environmental issues can no longer be managed using formal systems alone. The ideas presented in this study are offered cautiously, as direct interventions are required to improve organizations' environmental performance.

Limitations

This study has certain limitations. First, this study only included articles indexed in the Scopus database published in English. Studies indexed in other databases or published in other languages were excluded. The results show that the maximum number of publications originated from China. There may have been articles in the Chinese language that were not considered. Future studies can also utilize other databases, such as Web of Science (WoS) and other languages, based on data retrieved from alternative databases. Although Scopus is the largest OCB-E database, it does not include all OCB-E-related publications. This study only investigated published articles. There may also be other document types not included in this study. Some of these include conference articles and theses containing articles on OCB-E. Second, the study was confined to OCB-E, limiting the research context. The third limitation of this bibliometric study is the sensitivity of the selection criteria and filters used to construct the sample. This may conceal relevant articles, depending on the search query employed. Searching the references of the selected articles may alleviate this side effect by revealing research not included in the sample, which might help understand the covered subject. Next, there could be multiple other environmental behaviors that could be a topic for further research. Further research could be conducted using sociograms to determine the relationship between OCB-E and variables in the field. Bibliometric analysis, an indicator of research performance, is important for citation analysis. Citation patterns vary significantly and depend on the type of research conducted (Nouri, 2022). For instance, reviews and methodology articles were cited more often. According to Wallin (2005), "bad scientific works" may be cited profusely rather than well-known deserving fundamental works. A few numerical metrics cannot define scientific merit. Kostoff (2002) believes citation analyses signify short-term research impacts and are attractive candidates for impact and quality. Considering that the research topic is recent, it is expected that this aspect will not be an issue for this study.

CONCLUSION

This study aimed to provide a macroscopic summary of the main characteristics of OCB-E based on bibliometric analysis. The prevalence and usefulness of bibliometric software based on artificial intelligence and professional and broad-based databases with literature volumes have made bibliometric analyses extremely popular. The concept of OCB-E was new and originated approximately two decades ago. The results show that research interest in OCB-E is gaining momentum. The number of citations grew steadily. However, growth is less encouraging than related topics, such as pro-environmental behavior and green human resource management. For instance, only 187 articles have been published in the past decade. This figure is not encouraging for topics such as OCB-E, which have immense potential in organizational settings. OCB-E can potentially become a prominent topic in organizational behavior in the near future as it could facilitate organizational sustainability. The study is significant because the findings provide a clear understanding of the research progress achieved in OCB-E, opening up further vistas for researchers to conduct empirical examinations in the field. The findings also helped to identify the fundamental influences of authors, journals, and references. Bibliometric analysis is ideal for summarizing and synthesizing the available field literature. The novelty of this study stems from the fact that it is one of the few bibliometric studies on OCB-E. This study, the first of its kind, will trigger future research. This methodology has some limitations. For example, data extracted from scientific databases such as Scopus are generally not prepared solely for bibliometric analysis, which could lead to inadvertent errors. Such errors can affect analysis when utilizing data. This study followed established selection criteria. Consequently, all duplications and replications were eliminated, and disparities within the selected studies were reduced, thereby boosting data quality. Since bibliometric analysis is quantitative and the connection between quantitative and qualitative outcomes is frequently ambiguous, bibliometric analysis could be unclear. This situation can be reversed by making qualitative assertions regarding bibliometric observations and supplementing them with content analysis. Future studies should follow this assumption to obtain better results. Furthermore, the study was based on literature accumulated over the past two decades. Therefore, overly ambitious assertions must be avoided when interpreting the findings. This study was conducted based solely on publications mined from the Scopus database. Future studies could consider using publications from other databases, such as the Web of Science, which would help widen the scope of the study.

AUTHOR CONTRIBUTIONS

M.M. Sulphey has conceived and designed the research; Performed the search; analyzed and interpreted the data; contributed materials, analysis tools and data. N.S. AlKahtani analyzed, interpreted the data. N.A.M. Senan interpreted the data; contributed materials, analysis tools and data. A.H.E. Adow contributed materials, analyzed and interpreted the data.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

ACA	Author cocitation analysis
CSV	Comma-separated values
ECB	Environmental citizenship behavior
EMS	Environmental management systems
EU	European Union
OB	Organizational behavior
OCB	Organizational Citizenship Behavior
OCB-E	Organization Citizenship Behavior for the Environment
US	United States

REFERENCES

Abramo, G.; D'Angelo, C.A.; Viel, F., (2011). The field-standardized average impact of national research systems compared to world average: The case of Italy. Scientometrics. 88(2): 599-615 **(17 pages).**

Adjei-Bamfo, P.; Bempong, B.; Osei, J.; Kusi-Sarpong, S., (2019). Green candidate selection for organizational environmental management. Int. J. Manpower. 41(7): 1081-1096 **(16 pages).**

Alt, E.; Spitzeck, H., (2016). Improving environmental performance through unit-level organizational citizenship behaviors for the environment: a capability perspective. J. Environ. Manage., 182(1): 48-58 **(11 pages)**.

Baas, J.; Schotten, M.; Plume, A.; Côté, G.; Karimi, R., (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. Quant. Sci. Stu., 1(1): 377–386 (**10 pages**).

Bauer, T.N.; Aiman-Smith, L., (1996) Green career choices: The influence of ecological stance on recruiting. J. Bus. Psycol., 10: 445–458 **(14 pages)**.

Bayer, A.E.; Smart, J.C.; McLaughlin, G.W., (1990). Mapping intellectual structure of a scientific subfield through author co-citations. J. Am. Soc. Inf. Sci., 41(6): 444–452 **(9 pages).**

Boiral, O., (2008). Greening the corporation through organizational citizenship behaviors. J. Bus. Ethics. 87: 221–236 **(16 pages)**.

Boiral, O.; Paillé, P., (2011). Organizational citizenship behaviour for the environment: measurement and validation. J. Bus. Ethics. 109: 431–445 **(15 pages)**.

Boiral, O.; Talbot, D.; Paillé, P., (2013). Leading by example: a model of organizational citizenship behavior for the environment. Bus. Strategy Environ., 24: 532–550 **(19 pages)**.

Boiral, O.; Paillé, P., (2012). Organizational citizenship behaviour for the environment: Measurement and validation. J. Bus. Ethics. 109(4): 431-445 **(15 pages)**.

Broadus, R.N., (1987). Toward a definition of "bibliometrics". Scientometrics. 12: 373–379 **(7 pages)**.

Channa, N.A.; Hussain, T.; Casali, G.L.; Dakhan, S.A.; Aisha, R., (2021). Promoting environmental performance through corporate social responsibility in controversial industry sectors. Environ. Sci. Pollut. Res., 28(18): 23273-23286 **(14 pages).**

Chiaburu, D.S.; Oh, I.S.; Berry, C.M.; Li, N.; Gardner, R.G., (2011). The five-factor model of personality traits and organizational citizenship behaviors: A meta-analysis. J. Appl. Psycol., 96(6): 1140–1166 **(27 pages)**.

Ciocirlan, C.E., (2017). Environmental workplace behaviors definition matters. Organ. Environ., 30(1): 51–70 **(20 pages)**.

Cucari, N.; Tutore, I.; Montera, R.; Profita, S., (2022). A bibliometric performance analysis of publication productivity in the corporate social responsibility field: Outcomes of SciVal analytics. Corporate Soc. Responsibility Environ. Manage., 30(1): 1–16 **(16 pages)**.

Cooper, I.D., (2015). Bibliometrics basics. J. Med. Lib. Assoc., 103: 217–218 **(2 pages)**.

Daily, B.F.; Bishop, J.W.; Govindarajulu, N., (2008). A conceptual model for organizational citizenship behavior directed toward the environment. Bus. Soc., 48(2): 243-256 **(14 pages)**.

D'Arco, M.; Marino, V., (2022). Environmental citizenship behavior and sustainability apps: An empirical investigation. Transforming Government: People Process Policy. 16(2): 185-202 **(18 pages)**.

De Groot, J. I.; Steg, L., (2008). Value orientations to explain beliefs related to environmental significant behavior. How to measure egoistic, altruistic, and biospheric value orientations. Environ. Behav., 40: 330-354 **(25 pages)**.

Dickersin, K.; Scherer, R.; Lefebvre, C., (1994). Systematic reviews: Identifying relevant studies for systematic reviews. Braz. Med. J., 309(6964): 1286-1291 **(6 pages)**.

Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W. M., (2021). How to conduct a bibliometric analysis: An overview and guidelines. J. Bus. Res., 133: 285–296 **(17 pages)**.

Eito-Brun, R., (2018). Visibility of the CryoSat mission in the scientific and technical literature: A bibliometric perspective. Adv. Space Res., 62:1626-1638 **(13 pages).**

Ellegaard, O.; Wallin, J.A., (2015). The bibliometric analysis of scholarly production: How great is the impact? Scientometrics. 105: 1809–1831 **(33 pages)**.

Erdogan, B.; Bauer, T.N.; Taylor, S., (2015). Management commitment to the ecological environment and employees: implications for employee attitudes and citizenship behaviors. Hum. Relat., 68(11): 1669-1691 **(23 pages)**.

Faisal, S., (2023). Green human resource management—A Synthesis. Sustainability. 15: 2259 **(21 pages)**.

Falagas, M.E.; Karavasiou, A. I.; Bliziotis, I.A., (2006). A bibliometric analysis of global trends of research productivity in tropical medicine. Acta Tropica, 99(2-3): 155-159 **(5 pages).**

Gaur, A.; Kumar, M., (2018). A systematic approach to conducting review studies: An assessment of content analysis in 25 years of IB research. J. World Bus., 53(2): 280–289 **(10 pages).**

Gora, A.A., (2019). The link between decision making process and performance: A Biblio. Anal. Manage. Econ. Rev., 4(2): 177-191 **(15 pages).**

Hameed, Z.; Khan, I.U.; Islam, T.; Sheikh, Z.; Naeem, R.M., (2020). Do green HRM practices influence employees' environmental performance? Int. J. Manpower. 41: 1061–1079 **(19 pages)**.

Hamsal, M.; Ichsan, M.; Wicaksono, H., (2023). The impact of environmental turbulence on business sustainability through organisational resilience and dynamic capabilities. Int. J. Bus. Environ., 14(4): 417–439 **(23 pages).**

Hanna, M.D.; Rocky Newman, W.; Johnson, P., (2000). Linking operational and environmental improvement through employee involvement. Int. J. Oper. Prod. Manage., 20(2): 148-165 **(18 pages).**

Herlina, M.G.; Lusia, E.; Rivaldo, (2023). Pro-environmental behaviour of big city employees in rasch model and sem outlook: A Preliminary Finding. E3S Web of Conferences. 388: 03036.

Hooi, L.W.; Liu, M.S.; Lin, J.J.J., (2021). Green human resource management and green organizational citizenship behavior: do green culture and green values matter? Int. J. Manpower. 43: 763–785 **(23 pages)**.

Huda, M.N.; Nawangsari, L.C.; Sutawidjaya, A.H., (2021). The factors that influence organizational citizenship behaviour for the environment. Int. Rev. Manage. Mark., 11(3): 85–95 **(11 pages).**

Jeong, Y.K.; Song, M.; Ding, Y., (2014). Content-based author co-citation analysis. J. Informetrics. 8(1): 197–211 **(15 pages)**.

Kalimullah, H.A.M.N.; Nawangsari, L.C.; Sutawijaya, A.H., (2019). Organization citizenship behavior for the environment at financial institutions. Dinasti Int. J. Edu. Manage. Soc. Sci., 1(2): 138–149 **(12 pages)**.

Kalamas, M.; Cleveland, M.; Laroche, M., (2014). Pro-environmental behaviors for thee but not for me: green giants, green Gods, and external environmental locus of control., J. Bus. Res., 67: 12-22 (**11 pages**).

Khalid, S.A.; Abdul Rahman, N.; Mat Noor, A.N., (2022). Organizational citizenship behavior for the environment among undergraduates. Int. J. Acad. Res. Bus. Soc. Sci., 12(3): 220 –232 **(13 pages)**.

Khan, N.U.; Irshad, A.; Ahmed, A.; Khattak, A., (2021). Do organizational citizenship behavior for the environment predict triple bottom line performance in manufacturing firms? Bus. Process Manage. J., 27(4): 1033-1053 **(21 pages).**

Khan, N.U.; Bhatti, M.N.; Obaid, A.; Sami, A.; Ullah, A., (2020). Do green human resource management practices contribute to sustainable performance in manufacturing industry?. Int. J. Environ. Sustainable Dev., 19(4): 412-432 (**21 pages**).

Kim, A.; Kim, Y.; Han, K.; Jackson, S.E.; Ployhart, R.E., (2014). Multilevel influences on voluntary workplace green behavior: Individual differences, leader behavior, and coworker advocacy. J. Manage., 43: 1335-1358 **(24 pages)**.

Kostoff, R.N. (2002). Citation analysis of research performer quality. Scientometrics, 53: 49–71 **(23 pages).**

Lamm, E.; Tosti-Kharas, J.; King, C.E., (2015). Empowering employee sustainability: Perceived organizational support toward the environment. J. Bus. Ethics. 128: 207-220 **(14 pages)**.

Lamm, E.; Tosti-Kharas, J.; Williams, E.G., (2013). Read this article, but don't print it: Organizational citizenship behavior toward the environment. Group Organ. Manage., 38(2): 163–197 **(34 pages).**

Lee, K.; Allen, N.J., (2002). Organizational citizenship behavior and workplace deviance: The role of affect and cognitions. J. Appl. Psychol., 87(1): 131–142 **(11 pages).**

Liu, X.; Yu, X.; Xing, W., (2022). Green product innovation via green transformational leadership and employees' ocbe: The moderating role of green organizational climate–empirical evidence from China' manufacturing enterprises. Pol. J. Environ. Stud., 31: 4487–4498 **(12 pages)**.

Liu, T.T., (2017). CSR and organizational citizenship behavior for the environment in hotel industry. Int. J. Contemp. Hospitality Manage., 29(3): 2867-2900 **(34 pages)**.

Lu, H.; Cai, S.; Liu, Y.; Chen, H., (2022). How GHRM impacts employee OCBE: The role of emotions and value discrepancy. Int. J. Manpower. 44(2): 318-333 (**16 page**s).

Liu, Z.; Mei, S.; Guo, Y., (2020). Green human resource management, green organization identity and organizational citizenship behavior for the environment: the moderating effect of environmental values. Chinese Manage. Stud., 15(2): 290-304 **(14 pages)**.

Liu, F.; Qi, M., (2022). Enhancing organizational citizenship behaviors for the environment: Integrating social identity and social exchange perspectives. Psychol. Res. Behav. Manaage., 15: 1901–1914 (**14 pages**).

Lülfs, R.; Hahn, R., (2013). Corporate greening beyond formal programs, initiatives, and systems: A conceptual model for voluntary pro-environmental behavior of employees. Eur. Manage. Rev., 10: 83-98 **(16 pages)**.

Makarius, E.E.; Mukherjee, D.; Fox, J. D.; Fox, A.K., (2020). Rising with the machines: A sociotechnical framework for bringing artificial intelligence into the organization. J. Bus. Res., 120: 262–273 **(12 pages)**.

Mateen, A.; Bilal, A.R.; Khushi, M.A., (2023). Unveiling the influence mechanism between green relational capital and social sustainability outcomes. Int. J. Bus. Environ., 14(2): 145-163 **(19 pages)**.

McCain, K.W., (1990). Mapping authors in intellectual space: A technical overview. J. Am. Soc. Inf. Sci., 41(6): 351–359 **(9 pages).**

Miles, D.E.; Borman, W.E.; Spector, P.E.; Fox, S., (2002). Building an integrative model of extra role work behaviors: A comparison of counterproductive work behavior with organizational citizenship behavior. Inter. J. Select. Assess., 10(1-2): 51–57 **(7 pages)**.

Moghadam, H.; Samimi, M., (2022). Effect of condenser geometrical feature on evacuated tube collector basin solar still performance: Productivity optimization using a Box-Behnken design model. Desalination, 542: 116092 **(8 pages).**

Moral-Munoz, J.A.; López-Herrera, A.G.; Herrera-Viedma, E.; Cobo, M.J., (2019). Science mapping analysis software tools: a review. in: Springer handbook of science and technology indicators. Springer Int. Publishing, Cham., 159185 **(27 pages)**.

Mustak, M.; Salminen, J.; Pl´e, L.; Wirtz, J., (2021). Artificial intelligence in marketing: Topic modeling, scientometric analysis, and research agenda. J. Bus. Res., 124: 389404 **(15 pages).**

Neessen, P.C.; de Jong, J.P.; Cani€els, M.C.; Vos, B., (2021). Circular purchasing in Dutch and Belgian organizations: the role of intrapreneurship and organizational citizenship behavior towards the environment, J. Cleaner Prod., 280: 1-13 **(13 pages)**.

Norton, T. A.; Parker, S. L.; Zacher, H.; Ashkanasy, N. M., (2015). Employee green behavior: A theoretical framework, multilevel review, and future research agenda. Organ. Environ., 28: 103-125 **(18 pages).**

Nouri, J., (2022). Editorial, Global J. Environ. Sci. Manage., 8(1) 1-3 **(3 pages).**

Ortiz-Avram, D.; Ovcharova, N.; Engelmann, A., (2023). Dynamic capabilities for sustainability: Toward a typology based on dimensions of sustainability-oriented innovation and stakeholder integration. Bus. Strat. Environ., 1-36 **(36 pages)**.

Osbaldiston, R.; Schott, J., (2012). Environmental sustainability and behavioral science: Meta-analysis of proenvironmental behavior. Environ. Behav., 44: 257-299 (**43 pages**).

Pham-Duc, B.; Tran, T.; Huu Hoang, D.; Bao Do, C., (2022). Global scientific literature on human resource development: A bibliometric analysis using Scopus database. Euro. J. Train. Dev., 47(7/8): 846–861 **(16 pages).**

Paillé, P.; Boiral, O.; Chen, Y., (2013). Linking environmental management practices and organizational citizenship behaviour for the environment: A social exchange perspective. Int. J. Hum. Res. Manage., 24(18): 3552–3575 **(24 paper).**

Paillé, P.; Meija-Morelos, J.H., (2019). Organisational support is not always enough to encourage employee environmental performance. The moderating role of exchange ideology. J. Cleaner Prod., 220: 10611070 **(10 pages)**.

Paillé, P.; Chen, Y.; Boiral, O.; Jin, J., (2013). The impact of human resource management on environmental performance: An employee-level study. J. Bus. Ethics. 121(3): 451-466 **(16 pages)**.

Paillé, P.; Raineri, N.; Boiral, O., (2017). Environmental behavior on and off the job: A configurational approach. J. Bus. Ethics, 158(1): 253-268 **(16 pages)**.

Patrasc-Lungu, A.; Iliescu, D., (2022). Goal self-concordance mediates the relation of core self-evaluations with organizational citizenship behavior but not with environmental organizational citizenship behavior. Psihologia Resurselor Umane. 20(2): 112–130 **(19 pages)**.

Priadi, A.; Fatria, E.; Nadiroh, S.D.; Oktaviani, A., (2018). Environmental citizenship behavior (the effect of environmental sensitivity, knowledge of ecology, personal investment in environmental issue, locus of control towards students' environmental citizenship behavior). E3S Web of Conferences, 74: 08002.

Pritchard, A., (1969), Statistical bibliography or bibliometrics. J. Doc., 25(4): 348-349 **(2 pages)**.

Raineri, N.; Paillé, P., (2016). Linking corporate policy and supervisory support with environmental citizenship behaviors: The role of employee environmental beliefs and commitment. J. Bus. Ethics. 137(1): 129148 **(20 pages)**.

Ramus, C.A., (2001). Organizing support for employees: Encouraging creative ideas for environmental sustainability. Calif. Manage. Rev., 43(3): 85–103 **(19 pages)**.

Ramus, C.A.; Killmer, A.B., (2007). Corporate greening through prosocial extrarole behaviours – a conceptual framework for employee motivation. Bus. Strategy Environ., 16(8): 554-570 **(17 pages)**.

Ramus, C.A.; Steger, U., (2000). The roles of supervisory support behaviors and environmental policy in employee ''Ecoinitiatives'' at leadingedge European companies. Acad. Manage. J., 43(4): 605–626 **(22 pages).**

Ren, S.; Tang, G.; Kim, A., (2020). OCB-E among Chinese employees of different contract types. Employee Relat., 44(3): 609–628 **(21 pages)**.

Robertson, J.L.; Barling, J., (2017). Toward a new measure of organizational environmental citizenship behavior. J. Bus. Res., 75: 57–66 **(10 pages)**.

Rousseau, R., (2014). Forgotten founder of bibliometrics. Nature. 510, 218 **(1 page).**

Ruiz-Palomino, P.; Martínez-Cañas, R., (2014). Ethical culture, ethical intent, and organizational citizenship behavior: The moderating and mediating role of person-organization fit. J. Bus. Ethics. 120: 95-108 **(14 pages).**

Rupp, D.E.; Mallory, D.B., (2015). Corporate social responsibility:

Psychological, person-centric, and progressing. Annu. Rev. Organ. Psychol. Organ. Behav., 2(1): 211-236 **(26 pages)**.

Samimi, M.; Moghadam, H., (2024). Modified evacuated tube collector basin solar still for optimal desalination of reverse osmosis concentrate. Energy, 289: 129983 **(8 pages).**

Samimi, M.; Shahriari-Moghadam, M., (2023). The Lantana camara L. stem biomass as an inexpensive and efficient biosorbent for the adsorptive removal of malachite green from aquatic environments: kinetics, equilibrium and thermodynamic studies. Int. J. Phytoremediation, 25(10): 1328-1336 **(9 pages).**

Samimi, M.; Nouri, J., (2023). Optimized Zinc Uptake from the Aquatic Environment Using Biomass Derived from Lantana Camara L. Stem, Pollution, 9(4): 1925-1934 **(10 pages).**

Samimi, M.; Mohammadzadeh, E.; Mohammadzadeh, A., (2023). Rate enhancement of plant growth using Ormus solution: optimization of operating factors by response surface methodology. Int. J. Phytoremediation, 25(12), 1636-1642 **(7 pages).**

Sarid, A.; Goldman, D., (2021). A value-based framework connecting environmental citizenship and change agents for sustainability—Implications for education for environmental citizenship. Sustainability, 13(8): 4338, 1-19 **(19 pages)**.

Shafaei, A.; Nejati, M., (2023). Green human resource management and employee innovative behaviour: Does inclusive leadership play a role? Person. Rev., 1-22 **(22 pages)**.

Steg, L.; Bolderdijk, J. W.; Keizer, K.; and Perlaviciute, G., (2014). An integrated framework for encouraging pro-environmental behaviour: The role of values, situational factors and goals. J. Environ. Psychol., 38: 104-115 **(7 pages).**

Stern, P.C., (2000). Toward a coherent theory of environmentally significant behavior. J. Soc. Issu., 56: 407-424 **(19 pages).**

Sulphey, M.M.; Al-Kahtani, N.S.; Senan, N.A.M.; Adow, A.H.E., (2023). An Examination of a few Antecedents of Green Creativity Using Structural Equation Modeling. Creativity Stud. 16: 509–528 **(20 pages).**

Sulphey, M.M., (2022). A meta-analytic literature study on the relationship between workplace spirituality and sustainability. J. Reli. Health. 1-22 **(22 pages)**.

Sulphey, M.M; Faisal, S., (2021). Connectedness to Nature and Environmental Concern as Antecedents of Commitment to Environmental Sustainability. Int. J. Energy Econ. Policy. 11(2): 208-219 **(12 pages)**.

Sulphey, M.M.; (2019). The present and future of Education for Sustainable Development (ESD): A fact sheet, Int. J. Environ. Workplace and Emp., 5(3): 220 – 234 **(15 pages)**.

Sulphey, M. M. (2017).; Towards sustainable forest management through enhancing safety of nature. J. Secur. Sustainability Issues. 6 (4), 703 – 710 **(8 pages)**.

Sulphey, M.M.; Safeer, M.M., (2017). Introduction to Environment Management, (4th Edition), New Delhi: PHI Learning Pvt. Ltd.

Syafrudin; Budihardjo, M.A.; Priyambada, I.B.; Haumahu, S.A.Q.; Puspita, A.S., (2023). Bibliometric analysis for sustainable food waste using multicriteria decision. Global J. Environ. Sci. Manage., 9(SI): 271-300 **(30 pages).**

Temminck, E.; Mearns, K.; Fruhen, L., (2015). Motivating employees towards sustainable behaviour. Bus. Strategy Environ., 24(6): 402-412 **(11 pages)**.

Terrier, L.; Kim, S.; Fernandez, S., (2016). Who are the good organizational citizens for the environment? An examination of the predictive validity of personality traits. J. Environ. Psychol., 48: 185–190 **(6 pages)**.

Tosti-Kharas, J.; Lamm, E.; Thomas, T.E., (2016). Organization OR environment? Disentangling employees' rationales behind organizational citizenship behavior for the environment. Organ. Environ., 30(3): 187–210 **(24 pages)**.

Tu, W.; Fang, J.; Fangyu, J.; Ci, Y., (2021). Bibliometric research in the field of artificial intelligence. Conference Series: J. Phys., 1883(1): 012165 **(8 pages).**

Urban, J.; Bahník, �.; Braun Kohlová, M., (2023). Pro-Environmental Behavior Triggers Moral Inference, Not Licensing by Observers. Environ. Behav., 55(1-2): 74-98 **(30 pages).**

Van der Werff, E.; Steg, L.; Keizer, K., (2013). The value of environmental self-identity: The relationship between biospheric values, environmental self-identity and environmental preferences, intentions and behaviour. J. Environ. Psychol., 34: 55-63 **(9 pages)**.

Van Eck, N.; Waltman, L.; Noyons, E.; Buter, R., (2010). Automatic term identification for bibliometric mapping. Scientometrics. 82(3): 581-596 **(16 pages)**.

Van Raan, A., (2003). The use of bibliometric analysis in research performance assessment and monitoring of interdisciplinary scientific developments. TATuP - Zeitschrift für Technikfolgenabschätzung in Theorie und Praxis. 12: 20�29 **(10 pages)**.

Yuriev, A.; Boiral, O.; Francoeur, V.; Paille, P., (2018). Overcoming the barriers to pro-environmental behaviors in the workplace: a systematic review. J. Clean Prod., 182, 379-394 **(16 pages)**.

Wallin, J.A., (2005). Bibliometric methods: Pitfalls and possibilities. Basic Clin. Physiol. Pharmacol Toxicol, 97(5): 261–275 **(13 pages)**.

Wang, M., Yu, T.; Ho, Y., (2009). A bibliometric analysis of the performance of water research. Scientometrics. 84(3): 813-820 **(8 pages)**.

Wang, X.; Zhou, K.; Liu, W., (2018). Value congruence: A study of green transformational leadership and employee green behavior. Front. Psychol., 9: 1-8 **(8 pages)**.

White, H.D.; Griffith, B.C., (1981). Author cocitation: A literature measure of intellectual structure. J. Am. Soc. Inf. Sci., 32: 163–171 **(9 pages)**.

Zientara, P.; Zamojska, A., (2018). Green organizational climates and employee pro-environmental behavior in the hotel industry. J. Sustainable Tourism. 26(7): 1142-1159 **(18 pages)**.

Zhao, H.; Zhou, Q., (2020). Socially responsible human resource management and hotel employee organizational citizenship behavior for the environment: a social cognitive perspective, Int. J. Hospitality Manage., 102749 **(13 pages).**

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REVIEW PAPER

Life cycle assessment of agricultural waste recycling for sustainable environmental impact

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ABSTRACT

Agricultural waste recycling is crucial for sustainable farming operations and farming practices. Life cycle assessment has emerged as an innovative and comprehensive viewpoint that considers the entire recycling process to evaluate the potential and true implications of agricultural waste recycling. This study considered methods for recycling different agricultural waste streams, such as crop waste, animal manure, pruning materials, and by-products and subsequent uses. Furthermore, the life cycle assessment method was used to investigate the process of handling agricultural waste, from collection and recycling to final usage in the agricultural system. Environmental impact categories, including greenhouse gas emissions, energy usage, eutrophication, acidification, and land use, were evaluated to determine their potential effects on climate change, resource depletion, and ecosystem health. The results were compared with those of 31 studies that analyzed the potential environmental impacts of agricultural waste management. Various methods initially developed and implemented for agricultural waste landfilling methods have now changed to energy-generating sources, such as biochar, biogas, briquettes, and various energy production methods. Furthermore, composting, a popular method of recycling agricultural waste, significantly lowers greenhouse gas emissions and energy use compared to traditional waste disposal techniques. The study also examines cutting-edge technologies, such as anaerobic digestion and biomass-to-energy conversion, highlighting their potential to manage agricultural waste and being a sustainable energy source. These findings indicate potential environmental advantages in terms of decreased greenhouse gas emissions and fossil fuel consumption, leading to a circular economic approach for agriculture. When integrating agricultural waste, including composting, anaerobic digestion, and pyrolysis, biochar is highlighted as a waste recycling method that is promising for sustainable waste management. In addition to efficiently managing agricultural waste, these technologies help generate electricity and sequester carbon, thereby advancing the objectives of climate change mitigation and circular economy. Although life cycle assessment has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be challenging to gather complete and accurate data to assess the entire lifecycle of agricultural waste management technology. The direct environmental effects of waste management are frequently the focus of life cycle assessment studies, but they may overlook secondary effects such as indirect land use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis.

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INTRODUCTION

Pursuing sustainable practices has become essential across industries due to escalating environmental problems. As a foundational element of civilization, agriculture significantly impacts the planet's future fate. However, given that traditional agricultural methods adversely affect the environment, it is important to look for alternatives that balance agricultural output and environmental stewardship (Eyhorn *et al.*, 2019). A paradigm shift in approaching agricultural operations is necessary in light of the world's expanding population, climate change, and loss of natural resources. Conventional approaches caused detrimental environmental effects such as soil erosion, water pollution, and greenhouse gas (GHG) emissions, frequently accompanied by ineffective waste management (Sharma *et al.*, 2023). Sustainable agriculture can potentially help create a more sustainable and resilient global future. There is a growing understanding that recycling and circular economy strategies may transform waste into valuable resources (Kurniawan *et al.*, 2022). An innovative and comprehensive perspective that considers the complete life cycle of these recycling processes is required to evaluate the potential and implications of recycling agricultural waste. The method, known as "Life Cycle Thinking," explains the extensive environmental effects of recycling agricultural waste and provides insights into sustainable practices (Dahiya *et al.*, 2020; Zeug *et al.*, 2023). The core idea of "sustainability" is life cycle thinking, an original and comprehensive strategy that goes beyond conventional linear evaluations. Life Cycle Thinking provides a thorough understanding of the environmental impact at every stage by considering the entire life cycle of agricultural waste from its origin through final recycling or disposal (Hauschild *et al.*, 2020; Puspita *et al.*, 2023), and it helps create transformational opportunities to reduce unfavorable effects and improve sustainable behaviors. Furthermore, Life Cycle Thinking gives a precise and comprehensive assessment by considering the entire life cycle of trash from its initial generation through its eventual reuse or disposal. Recycling techniques using this strategy are suitable for the environment but have uncovered potential trade-offs (Wahyono *et al.*, 2023; Wu *et al.*, 2021). Additionally, Life Cycle Thinking ensures that decision-makers are aware of the long-term effects of their decisions, promoting the development of intelligent policies and practices. Waste can be diverted from conventional disposal procedures and reused to reduce environmental harm and improve the circular flow of resources within agricultural systems. Recycling agricultural waste is a practical method that balances environmental protection with human advancement, paving the way for a resilient and regenerative planet. Life-cycle assessment (LCA) is a robust framework that directs research and has an ambitious purpose and clear objectives. The LCA technique analyzes the entire life cycle of agricultural waste recycling (Gilani *et al.*, 2023). While various studies have analyzed the potential environmental impacts of various agricultural waste management methods, no studies have analyzed and compared each method completely in Asian nations. Therefore, this study's results can help Asian countries consider adding agricultural waste management methods and assess the environmental effects of each stage, revealing vital information that guides sustainable decision-making. Furthermore, this study aims to enable readers to holistically analyze the implications of recycling agricultural waste, noting its broader environmental effects. Moreover, this study aims to uncover the potential for sustainable practices, promote circular economy principles, educate policy decisions, increase stakeholder engagement, and contribute to global sustainable development goals using LCA methodology. Finally, this study aims to promote and help implement sustainable agricultural waste recycling procedures to encourage a more peaceful coexistence between agriculture and the environment. This study was conducted in an Asian country in 2023.

METHODOLOGY

State of the art and challenges for agricultural waste management LCA in answering sustainable concept

Agricultural land use produces significant agricultural waste, such as crop leftovers, animal manure, and trash from food processing (Rani *et al.*, 2023). Improper agricultural waste management can have adverse environmental effects, including soil, water, and air pollution, as well as land degradation; therefore, effective agricultural waste management is crucial (Koul *et al.*, 2022). Regarding agricultural waste management, sustainability refers to balancing human needs and preserving and protecting the

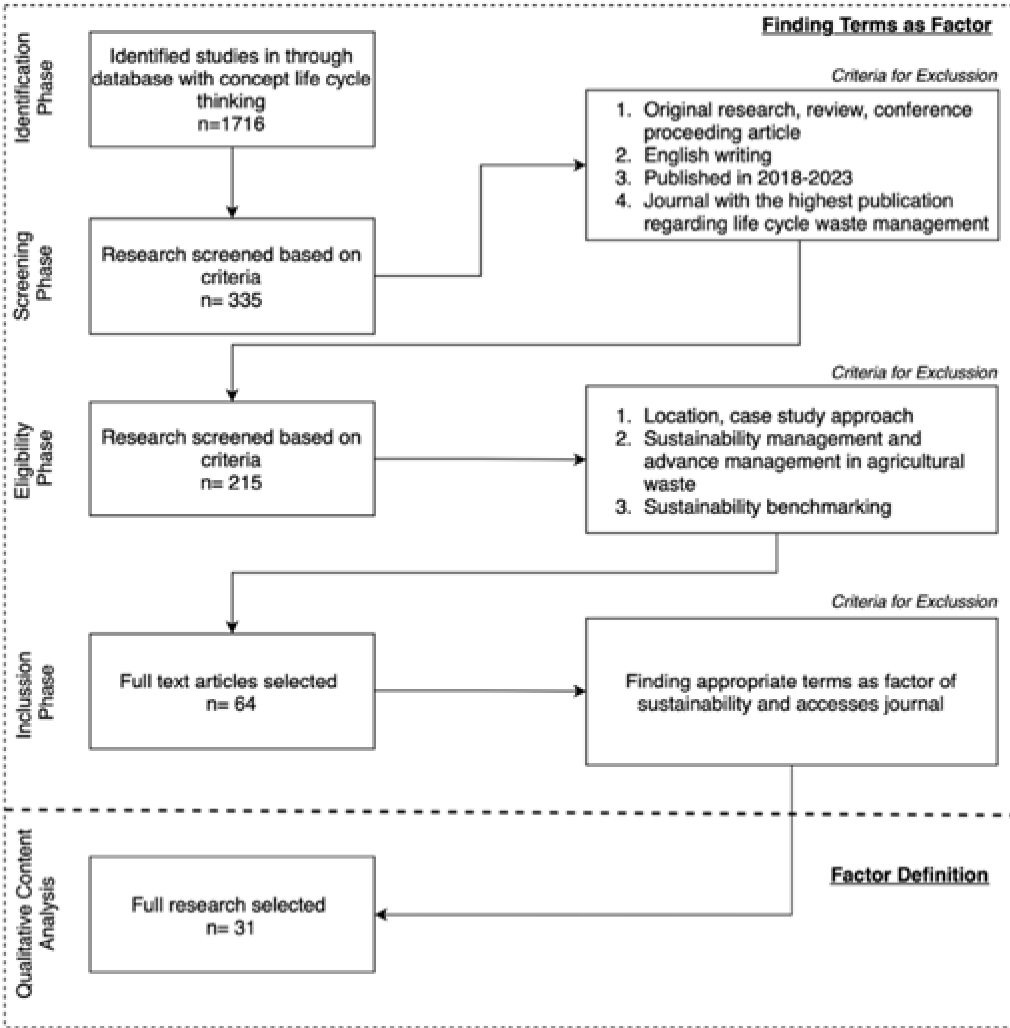

Fig. 1: Steps to find, identify, and define agricultural waste management with a sustainable concept

environment. This entails techniques that enhance the social and economic well-being of farmers and communities around them and reduce harmful environmental effects (Nigussie *et al.*, 2021). The LCA method is crucial for determining the environmental impact of a process or product from the perspective of production to final disposal. Regarding managing agricultural waste, LCA makes it possible to thoroughly assess the environmental effects of alternative waste treatment choices, including creating new treatment techniques and discovering potential enhancements in environmental performance (Llorach-Massana *et al.*, 2023). A life-cycle thinking strategy is related to LCA and is advocated for managing agricultural waste. Life cycle gas emissions conserve natural resources such as land and water and boost soil fertility (Adekomaya and Majozi, 2022; Mondal and Palit, 2022). It is possible to develop efficient and sustainable policies and activities to address sustainability in managing agricultural waste by incorporating life-cycle thinking and LCA.

Selection criteria of research LCA review

This study focuses on LCA studies on the management of agricultural waste produced from each agricultural process in Fig. 1. This study utilizes SCOPUS and Google

Table 1: Traditional agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
Qatar	FU: 1 ton Method: CML 2 baseline 2000 Model: Simapro Waste type: agriculture general waste	S1: WC S2: AD S3: WC, AD	1. ADp 2. GWP 3. OD 4. HT 5. PO 6. AP 7. EP	In terms of overall impact, the use of fossil fuels for transportation accounts for around 60 percent (%) of the emissions produced. Composting follows with 40% of the emissions produced, particularly in terms of possible global warming.	Al-Rumaihi *et al.,* 2020)
China	FU: 1 Mt Method: Ecoinvent 3.2 Model: OpenLCA Waste type: Dairy manure	S1: AD S2: COMP S3: SS-AD, COMP	1. ADp 2. GWP 3. EP 4. RD	The combined GWP of solid-state AD and composting, which is -2900 kg CO_2 eq/t of dairy manure, was the lowest. This figure is almost 14.8 times lower than that of the current status, which is liquid AD of dairy manure.	Li *et al.,* 2018)
Turkey	FU: 1 ton Method: Edip 2003 Model: Gabi 5 Waste type: Agriculture and organic fertilizer	S1: AD S2: GS S3: LF	1. AP 2. AE 3. GWP 4. POF 5. SOD	By removing it from the region's traditional landfilling waste management system, the sustainability of energy production from agricultural and farm waste, via AD, was further strengthened.	Nayal *et al.,* 2016)
China	FU: 1 ton Method: CML 2000 Model: Simapro Waste type: Pig Manure	S1: AD S2: BS S3: Ds	1. GWP 2. AP 3. EP 4. HT 5. ADp 6. OD	The findings imply that comprehensive digestate reuse and biogas use (heating, lighting, and fuel) from AD are equally important in the system's overall energy production and play a significant role in systemic greenhouse gas reduction.	Chen *et al.,* 2012)
Beijing	FU: 1 ton Method: IPCC, CML, Ecoinvent Model: Simapro Waste type: Mixed manure	S1: BS	1. GHG	Hopefully, by improving fermentation efficiency and coordinating the operation of biogas digesters, the linked system can be maximized.	Chen and Chen, 2013)
Vietnam	FU: 1 ton, 100 kg Method: Recipe 2008 Model: Simapro Waste type: liquid manure, solid manure	S1: BS	1. GWP 2. FD 3. FE 4. MAE	Biogas digesters could help to mitigate the effects of global warming if methane emissions are kept to a minimum, according to a sensitivity study.	Vu *et al.,* 2015)
China	FU: 1 ton Method: Ecoinvent, Eco-indicator 99, IPCC 2007 Model: Simapro Waste type: agricultural waste	S1: BS	1. GWP 2. OD 3. AD 4. EP	According to the findings, the production of biogas has a positive impact on artificial environments while having a negative impact on GWPs. With time, its detrimental effects on GWPs become more pronounced.	Wang *et al.,* 2016)
Singapore	FU: 1000 ton Method: NA Mode: Gabi Waste type: NA	S1: INC S2: AD	1. AD 2. EP 3. GWP 4. HT 5. MAE 6. OD	The sensitivity study also showed that by reducing water use, reducing gas engine emissions, and diverting as much FW from incineration plants to AD plants as possible, better environmental profiles might be attained.	Tong *et al.,* 2018)

Continued Table 1: Traditional agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
Indonesia	FU: 1 ton Method: IPCC 2013, Impact 2002+ Model: Simapro Waste type: Animal manure	S1: COMP S2: BS S3: COLT-BS (A)	1. GWP 2. AP 3. EP 4. HT	The findings given here suggest that the GWP was the most important factor in the environmental impact evaluation of the POME. COLT-Biogas A combined with communication posting was found to be more environmentally beneficial than the other combinations in terms of GWP.	Nasution *et al.,* 2018)
Malaysia	FU: 1 ton Method: CML 2001 Model: Simapro Waste type: Agro residue	S1: COMP S2: LF	1. OD 2. GWP 3. AP 4. EP 5. ECt	The completed compost is demonstrated to satisfy Malaysia's requirements for organic fertilizer, proving the viability of this affordable method.	Keng *et al.,* 2020)
India	FU: 1 ton Method: CML 2001 Model: Simapro Waste type: Agro residue	S1: PRs S2: Ln S3: Cs	1. GWP	The development of biofuel processing, however, has a number of challenges in addition to the advantages mentioned above, such as scientific, technological, economic, environmental, safety, depository, policy, and so on. Therefore, thorough R&D is required to overcome these obstacles. However, these negative effects can be lessened by technological development and careful planning.	Rahimi *et al.,* 2022)
Vietnam	FU: 1 ton Method: Recipe Model: Gabi Waste type: Organic manure, corn waste	S1: PRs S2: Br	1. GHG	Due to its low cost, high efficiency, simplicity of usage, ecological integrity, and reliability in terms of public safety, biochar made from agricultural waste biomass may be a suitable replacement for managing pollutants.	Nguyen *et al.* , 2019)
China	FU: 1 ton Method: Gabi Model: NA Waste type: Oil palm kernel shell and empty fruit bunches	S1: Co- PRs	1. GWP 2. HT 3. TETP 4. AP	In summary, these studies can serve as a resource and simple methodology for persons who are interested in advocating the use of co-pyrolysis of agricultural waste and promoting product industrialization.	Mo *et al.,* 2022)
Indonesia	FU: 1 ton Method: Gabi Model: CML-2001 Waste type: Coconut shells	S1: AC	1. GWP 2. HT 3. AP	The analysis of alternative scenarios suggests that by reducing the electrical energy consumptions in the process units of crushing and tumbling as well as by using electrical energy from renewable sources, such as biomass, the sustainability of activated carbon production in Indonesia could be greatly improved, reducing the contribution to global warming and local human toxicity. This would contribute to a reduction of 80% in global warming and a 60% decrease in the local impact to human toxicity.	Arena *et al.,* 2016)

Continued Table 1: Traditional agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
North Vietnam	FU: 1 ton Method: Simapro Model: IPCC 2006 Waste type: Rice straw and husk	S1: OB S2: Br	1. CF	The findings suggest that the climate consequences of these double rice cropping systems in Vietnam can be reduced by stopping the burning of crop leftover in the field and using residues to generate biochar for application to soils.	Mohammadi *et al.,* 2016)
Vietnam	FU: 1 Mt Method: Simapro Model: IPCC 2006 Waste type: Rice husk	S1: PRs, Br S2: Br, COMP	1. GWP	The findings of this LCA analysis suggest that, in comparison to open burning of rice husks during both the spring and summer rice cropping seasons, using rice husks for biochar in biochar-compost (COMBI) systems can improve climate change and health effects.	Mohammadi *et al.,* 2017)
China	FU: 1 Mt Method: Na Model: MUIO-LCA model Waste type: Feedstock	S1: Cr S2: Cr, Br S3: Cr, Dfp S4: Cr, Bb	1. GHG	The outcomes showed that Cr-Bb outperformed the other two technologies in terms of energy generation and air pollution reduction. Efficiency in energy conversion was proposed as a crucial variable in assessing the possibility for producing bioenergy and enhancing the environment.	Dai *et al.,* 2020)
Japan	FU: 1,34 ton Method: NA Model: NA Waste type: Manure	S1: COMP	1. GHG	On farmland on livestock farms, liquid materials (wastewater or slurry) could be applied.	Haga, 2021)
Indonesia	FU: 1 ton Method: NA Model: NA Waste type: General agricultural waste	S1: AF	1. Social 2. Economy	Using alternative agricultural waste as animal feed, it is possible to minimize agricultural waste, which has not previously been widely employed, and provide animal feed for the following six months in just 27 days.	Mufti and Fathurahman , 2022)

Scholar and the keywords "evaluation of the life cycle of agricultural waste management," publications for 31 LCA studies on agricultural management systems since 2012-2023 were obtained. The processing grouping is divided into two as described in Tables 1 and 2 namely traditional and advanced management using technology. Agricultural management is centered on one traditional management method that is analyzed and the use of new technology with a combination of traditional management, aims to compare the most efficient method of agricultural management. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method as a qualitative systematic review and science mapping as a quantitative and qualitative technique were used in literature studies to define and explore the aspects that influence sustainability in agricultural waste management. Fig. 1 depicts the approach used in the current investigation as a flowchart with PRISMA method. Data was gathered and examined utilizing a qualitative content analysis methodology, which offers insight into the circumstances surrounding the phenomenon under study and permits flexibility in research through the collection of descriptive and

Table 2: Advance agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
Bangladesh	FU: 1 kg Method: NA Model: NA Waste type: General agricultural waste	S1: AD S2: COMP S3; LF S4: INC S5: GS	1. Social 2. Economy 3. Politic	This study simply aims to increase understanding of the waste-related issues that have arisen in Bangladesh from various sources, and it then suggests a feasible model that may be used to achieve a zero-waste policy. The findings of this study are nevertheless intended to be applied by academics, scholars, researchers, policymakers, and practitioners to future endeavors to support the proposed model prior to the adoption of the zero-waste policy to attain sustainable development goals.	Ahmed *et al.,* 2023)
Indonesia	FU: 1 ton Method: Ecoinvent 3.1, Recipe Model: NA Waste type: Feedstock collection	S1: Br S2: Brq	1. GHG 2. Pm10 3. Sosial 4. Economy	In this instance, the benefits of carbon sequestration in the soil and the economic worth of improved agricultural production outweigh the drawbacks of biochar production for the environment and the expenditures associated with it.	Sparrevik *et al.,* 2014)
Philipines	FU: 1 kg Method: Ecoinvent 3.1 Model: Gabi Waste type: Rice straw, rice husk, coconut husk, coconut shell, cattle manure	S1: Cs S2: Gs S3: AD	1. GHG 2. MEP 3. HT 4. TETP 5. POF	The findings indicate that AD is generally the most environmentally friendly alternative, exceeding the competition in 14 of the 18 impact categories. Nearly all of the effects of AD are net-negative, indicating that they should be avoided. This is because manure is used more effectively than when it is dumped in water or left on the ground. The global warming potential of AD can range from 170% lower to 41% higher than that of the diesel generator, depending on the feedstock.	Aberilla *et al.,* 2019)
Thailand	FU: 1 ton Method: IPCC Model: Simapro Waste type: date palm waste	S1: Br	1. GWP	When the adsorption capacities of the two adsorbents were evaluated, it was discovered that biochar performs on par with activated carbon.	Shaheen *et al.,* 2022)

Continued Table 2: Advance agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
China	FU: 2,1 Mt Method: IPCC 2007 Model: OpenLCA Waste type: Straw	S1: PRs S2: Gs S3: Br S4: Brq	1. GWP	However indirect carbon abatement processes arising from biochar application could significantly improve the carbon abatement potential of the pyrolysis scenario. Likewise, increasing the agronomic value of biochar is essential for the pyrolysis scenario to compete as an economically viable, cost-effective mitigation technology.	Clare *et al.,* 2015)
China	FU: 1 ton Method: CML-2000 Model: Simapro Waste type: Agricultural straw	S1: Br S2: PRs	1. GWP 2. AD 3. AP 4. EP	A careful investigation revealed that the GWP categories are significantly impacted by the uncertainties of energy usage and agricultural straw yield.	Yang *et al.,* 2020)
Malaysia	FU: 1 ton Method: Recipe Model: Gabi Waste type: Organic manure, corn waste	S1: Gs S2: Ln S3: PRs S4: BS S5: Cs	1. GWP	Nevertheless, ongoing research is being done to address the gaps in the state-of-the-art technologies and boost their effectiveness and profitability.	Lee *et al.,* 2019)
Indonesia	FU: 1 ton Method: EASETECH Model: NA Waste type: Empty fruit bunch	S1: PRs	1. CF	For instance, some of the benefits of emissions reduction may be countered by the deforestation and land-use changes associated with oil palm farming. To maintain the overall sustainability of the biochar export program, it is critical to take into account and mitigate these negative effects.	Robb and Dargusch, 2018)
Thailand	FU: 1 ton Method: IPCC Model: Simapro Waste type: Manure and general agricultural waste	S1: BS	1. GWP 2. HT 3. FE 4. TE	Biomethane has the lowest well-to-wheel GHG emissions of all the biofuels (by less than one third).	Koido *et al.,* 2018)
Malaysia	FU: 1 ton Method: ReciPe Model:Simapro Waste type: Agricultural waste general	S2: LSS	1. GWP 2. HT	The production and milling of fresh fruit bunches for palm biodiesel and large-scale solar installations (electrical installation) aretwo environmental hotspots that have the potential to cause environmental burdens of up to 15–51% in terms of human non-carcinogenic toxicity, human carcinogenic toxicity, global warming, marine ecotoxicity, water	Phuang *et al.,* 2022)

Continued Table 2: Advance agricultural waste management

Research Study	Functional unit (FU), method, model & Waste type	Agriculture waste management	Impact assessment result of parameter	Critical findings	Sources
				consumption, and the scarcity of fossil fuels.	
China	FU: 1 ton Method: ReciPe Model: Simapro Waste type: Agro residue	S1: PRs S2: AD S3: GS S4: Cs S5: Ln	1. AP 2. EP 3. GWP	A popular management technique for reaching carbon neutrality in a circular economy, addressing both environmental and social problems, is to pyrolyze agricultural leftovers into biochar.	Zhu *et al.,* 2022)
China	FU: 2136 ton Method: Weighthing Model: Gabi Waste type: manure	S1: AD S2: GS S3: LBP	1. GWP 2. EP 3. AP 4. HT	According to the LCA, both large-scale (LBP) and BS plants demonstrated good environmental sustainability in terms of reducing pollutant emissions and producing clean energy.	Wang *et al.,* 2018)

visual data. The authors used the operator to search the SCOPUS database to find a suitable database covering the environmental effects of processing agricultural waste using the LCA approach. “TITLE-ABS-KEY (Agricultural Waste AND Agricultural Waste Recycle AND Life cycle assessment AND Asian).” The study was evaluated based on the following criteria: i) study area; ii) functional unit; iii) system boundary; iv) sensitivity analysis; v) environmental impact category; vii) potential comparison waste management strategy; and viii) key gaps and findings. Conference evaluations lack the requisite peer review to be recognized as a reliable source of information because they are not held to the same standards as journal articles. viii) Old conference evaluations: Conference reviews made before 2012-2023 may be regarded as out of date because more recent research has been undertaken. After reading the title, citation details, abstract, keywords, and the complete content, the author undertakes a thorough study analysis to establish credibility, dependability, and trustworthiness.

Review scheme

Critical evaluations focused on the fundamental elements of LCA for managing agricultural waste, such as the definition of objectives and scope, functional units, assumptions, selection of effect categories, and essential parameters/factors. Several LCA studies focusing on Asian nations have led to the discovery of these components. A logical ranking of the best technologies/policies was developed after categorizing the studies according to their distinctive nature and the treatment strategy used. Recommendations and the consequences of the best waste management techniques are provided based on numerous technological, environmental, and socioeconomic issues. This study is limited to agricultural waste, such as animal waste; agricultural wastewater, such as animal urine; and various plant residues (leaves, stems, and other plant parts remaining after harvest) with a gate-gate system (agricultural waste management). This selection aimed to ensure consistency in the life cycle analysis methodology. This includes selecting relevant inputs and outputs as well as modeling environmental impacts. This consistency supports the accuracy and sharpness of the research results. Therefore, collection and transportation are beyond the scope of this study.

Classification of LCA studied on basis economy analysis

In this subcategory of LCA studies, the environmental and economic impacts and various agricultural waste treatment solutions were compared. To determine the most effective and sustainable approach for handling agricultural waste in certain situations, researchers examined the lifecycle effects of various waste treatment techniques. This study was evaluated and classified based on technology and economics. It starts by classifying the technology, where the LCA study concentrates on assessing the technological aspects of agricultural waste management. This requires an evaluation of the effectiveness, performance, and environmental impact of various waste treatment systems, including waste-to-energy processes, anaerobic digestion, and composting. Furthermore, the economic aspects and evaluation of available alternative agricultural waste management methods are the main focus of LCA research in this category, requiring cost evaluations associated with various waste management approaches, comparing the financial feasibility of different treatment technologies, and exploring the potential savings or benefits of adopting more sustainable and affordable waste management techniques. Fig. 2 illustrates those various countries, from low- to high-income countries, have substantial differences in agricultural waste produced per person yearly, which also impacts the management costs. The average total agricultural spending per farm in the US in 2020 was $182,130, an increase of 2.6% over the average of $177,564 in 2019 (Smith *et al.*, 2020). Although these statistics cover many farm operations, a sizeable amount of these expenses may be devoted to waste management activities. Additionally, food waste is predicted to cost the US restaurant industry $162 billion annually (Blum, 2020; Read and Muth, 2021). The financial impact of the food industry's waste, which is closely tied to agricultural waste even though this figure is not solely devoted to managing agricultural waste, is apparent. Leaders in the recycling sector are investing in waste management strategies, indicating that money is being invested to create and implement effective waste management systems.

Mapping of the study area and evolution of LCA studies in Asia

Thirteen Asian countries meet the requirements for LCA analysis on agricultural waste management, and China is the most dominant country for agricultural waste management analysis. Despite China's tremendous industrial and technological developments, agriculture plays an important role in its economy. Waste management is a crucial issue that must be addressed because of the country's high dependence on agriculture. As a result, it also impacts a demanding environment where the

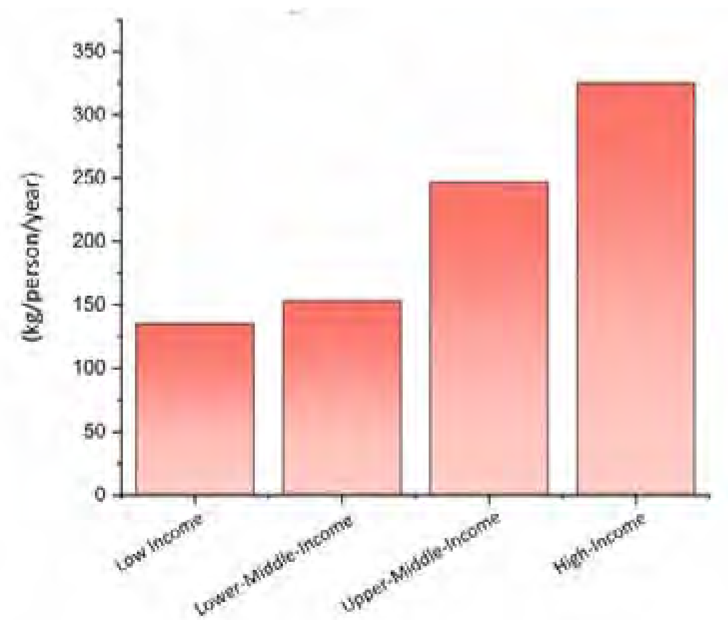

Fig. 2: Agricultural waste generation rate in different income group countries

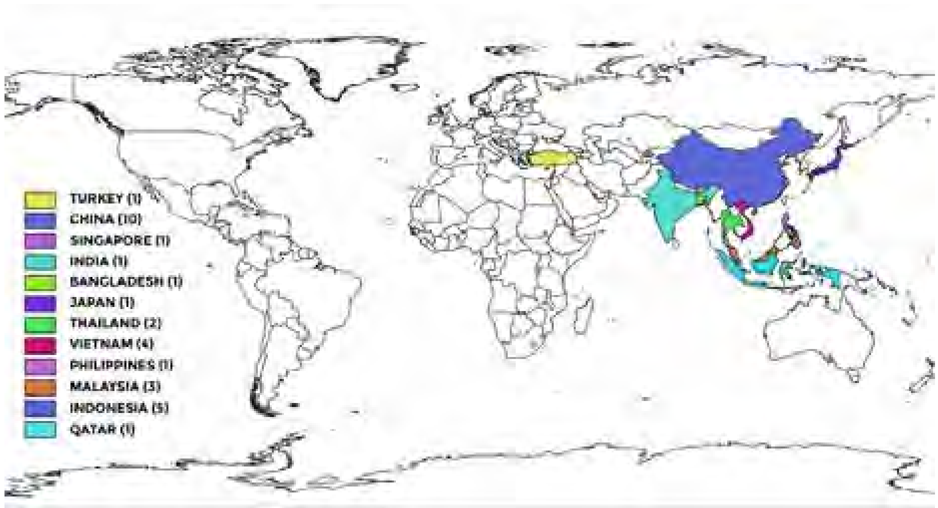

Fig. 3: Geographical distribution selected research

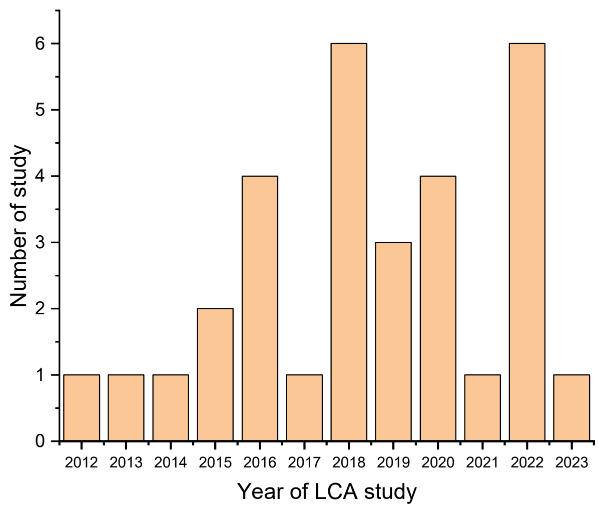

Fig. 4: Evolution time LCA studies (2012-2023)

handling of agricultural waste can negatively impact the environment, resulting in air and water pollution. China has stepped up its research efforts to identify sustainable solutions to this problem because of its growing awareness of environmental challenges. Fig. 3 shows the distribution of the LCA studies (shown in brackets) selected for evaluation in Qatar (1), China (9), Indonesia (5), Turkey (1), Beijing (1), Vietnam (4), Singapore (1), Thailand (2), Malaysia (3), India (1), Japan (1), Bangladesh (1), and Philippines (1). Most LCA were observed in 2020 and 2018, while the least LCA were observed between 2012-2014 and 2017, all of which had the same number of LCA, namely one study. The number of LCAs increased from 2016 to 2020, and the LCA studies identified in 2021 and 2023 were neither classified for analysis nor accessible. The number of LCAs is expected to increase in 2019 and 2022, as shown in Fig. 4. due to various factors such as the general public's understanding of environmental challenges, climate change, environmental degradation, and the scarcity of natural resources, which has grown over time. The need for LCA research is growing as more businesses, governments, and members of the public recognize the importance of gauging how products and activities affect the environment. Furthermore, laws and guidelines are being presented, and more nations and regulatory bodies are beginning to enact stricter environmental regulations, which may include demands that LCA be conducted on specific products. This motivates businesses and industries to conduct LCA research as part of their regulatory compliance and identify areas where their environmental performance can be enhanced. For the second Focus on Sustainability, throughout 2018–2020, sustainability rose to the top of the priority list for many organizations and industrial sectors. To make operations more sustainable, businesses are utilizing LCA as a valuable tool for assessing and controlling how human activities affect the environment.

Changes in the LCA can be attributed to waste-related issues in specific years, the amount of engagement in the scientific community, and the availability of functional units for projects involving municipal solid waste (MSW) management (Budihardjo *et al.*, 2023b; Yadav and Samadder, 2018). This trend highlights the significance of utilizing LCA to evaluate the environmental impacts of MSW management. The global uptake of LCA studies and the ISO 14044:2006 standard for LCA methodology are growing (Khandelwal *et al.*, 2019). Moreover, research, regulatory changes, and adoption of ISO standards have improved LCA implementation (Laurent *et al.*, 2020).

This review focuses on the main elements of LCA for MSW management, such as the definition of objectives and scope, functional units, assumptions, choice of effect categories, and critical parameters/factors. Several LCA investigations conducted in Asia led to the discovery of these components. A logical ranking of the best technologies/policies was developed after categorizing the research according to their distinctive characteristics and treatment methods. Recommendations and consequences of the best waste management techniques are based on numerous technological, environmental, and socioeconomic concerns.

Scope definition analysis

This section analyzes the vital aspects of the research results that have been collected, such as functional units, system limitations, the models used, the path categories analyzed, sensitive parameters, and the reasons for implementing the technology.

Functional unit

LCA includes functional units (FU) as fundamental vital points that require attention. The measured performance of the production system was used as a reference for the output produced (McAuliffe *et al.*, 2020; Haumahu *et al.,* 2023). The included LCA comparisons usually had the same FU to obtain fair results for each comparison of the technologies used. Limiting and having the same FU as a whole provides a general understanding of current waste management issues, necessary developments, processes that can be replaced with raw materials, and the replacement of fossil energy with natural energy, such as solar energy, so that it has an impact on sustainability, reduces management costs, and reduces emissions from an economic and environmental standpoint (Chen *et al.*, 2021; Saravanan *et al.*, 2021). Fig. 5 shows the FU for the cited agricultural waste management practices. The functional unit used in the studies cited in general was 1 ton (23 of 31 studies). Some used 1 Mt and more than 1 Mt (3 of 31 studies) and <1 ton and >1 ton for the remainder.

To accurately reflect the true intent of LCA and enable fair comparisons between various goods or services, the choice of a FU must be carefully considered (Corominas *et al.*, 2020). One ton is one of the most popular FU alternatives in LCA due to: i) industry standard: in certain industries or sectors, one ton is a commonly used measure of production or performance. For example, ton is the standard unit to report production quantities in industrially produced materials such as steel, cement, and paper; ii) Practical and easy to measure: Using ton as the FU can result in easier calculations and easier to perform in LCA analysis because it is easier to measure and compare; iii) Consistency: using ton as the FU allows for consistency in LCA analysis because different products or services can be compared on a similar scale with the same weight (ISO 14040, 2006; ISO 14044:2006). It is crucial to remember that FU selection should consider specific LCA objectives and encompass the entire extent of the goods or services being assessed (Marmiroli *et al.*, 2021). Depending on the goal and setting of the LCA, another FU may occasionally be more suitable. It is also important to understand the dynamic nature of the study, which means that over time, the procedures and methods

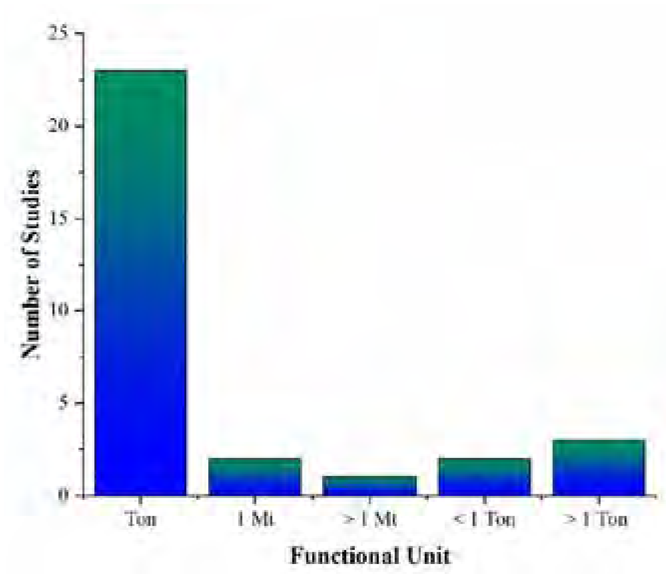

Fig. 5: Research on the use of functional units are distributed

employed in LCA may also change (Mio *et al.*, 2022). Consequently, a different set of FU may be chosen for each LCA instead of one ton.

System boundaries and use LCA methods

System constraints, commonly called "analytical constraints," are important for the LCA method's early phase. System boundaries are crucial factors affecting the overall results of an analysis (Bonilla-Alicea and Fu, 2019; Kajtaz, 2019). This is defined as the processing/management stage, which depends on what is being analyzed, including the operation phase, inputs, outputs, and operating time options for agricultural waste management (Sharma *et al.*, 2023). System boundaries determine the entry and exit of process units or component variables from the analysis performed (Abbasi *et al.*, 2022). This stage must consider the duration, scope, and study objectives, and the decision to exclude input/output processes must be explained (Onat and Kucukvar, 2022). System constraints should ensure that all relevant processes and the possibility of realizing their environments are considered in the evaluation. A proper definition of system boundaries carries the risk of offloading from one phase of the life cycle to another. Furthermore, the software or model used is a computer-based tool for collecting, organizing, and analyzing data, simulating systems from life cycle flows, and analyzing the impacts that will occur (Kenett *et al.*, 2023). Furthermore, LCA of various activities can be performed without the help of software. However, the experts greatly assisted in their work, such as obtaining, compiling, and analyzing various inventories. Common tools often used in LCA analysis, such as Simapro and Gabi, which have complete facilities as well as adequate choices for LCA analysis, such as characterizing and evaluating environmental impacts to examine life paths, such as urban waste management and agricultural waste, and can be accessed or subscribed to obtain unlimited premium services (Budihardjo *et al.*, 2023b). Other software has been developed specifically for LCA waste management, such as the Environmental Assessment System for Environmental Technologies (EASETECH), Integrated Waste Management, and Open LCA, and other newer experimental software programs, such as the MUIO-LCA model. Comprehensive data collection is required for LCA in all aspects of agricultural management, including the production of raw materials and the handling, processing, and disposal of waste (Trummer *et al.*, 2022). The general LCA analysis steps are as follows: i) Goal and scope determination: The program user determines the objectives of the analysis and specifies the parameters for the solid waste management system assessment and review;

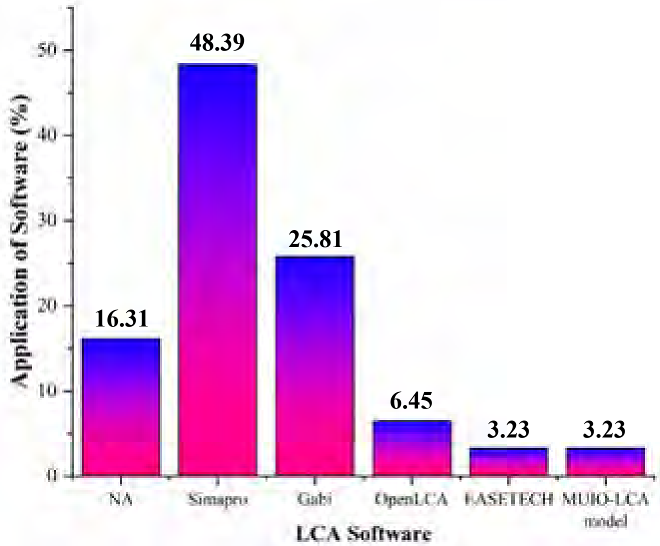

Fig. 6: Analysis of LCA research and growth

ii) Lifecycle inventory: Information on inputs and outputs is compiled and entered into a program. It contains information on the amount and type of energy consumed, raw material quantities and types, emissions, and other characteristics of each process; iii) Characterization of the environmental impact: The collected data explain how each phase of the waste management system affects the environment; and (iv) Interpreting the results: To understand the relative contributions of each stage of the waste management system to the overall environmental impact, the LCA results were assessed (ISO 14040, 2006 ; ISO 14044:2006). The software used in the cited research that will be compared and examined is shown in Fig. 6. To satisfy low-cost and environmentally friendly economic sectors, all LCA analyses seek to streamline agricultural waste management. With rates of 25.81%, 6.45%, and 48.39% for Gabi, Open LCA, and SimaPro, respectively, two studies that used the EASETECH and MUIO-LCA software also saw usage. However, in 16% of the studies, using software for analyzing environmental effects was left unexplained. Furthermore, 16% of studies did not employ any software for their environmental impact analyses for the following reasons: i) financial restrictions, licensed LCA software can be fairly priced, and research resources might not be enough to cover purchasing costs. Researchers may employ a manual approach or straightforward tools, such as spreadsheets or self-programming code, in such situations; ii) Flexibility and control. Under certain circumstances, it may be desirable to have complete control over the entire LCA process, including the figures and techniques employed. Researchers may feel constrained by their ability to alter or modify the existing software to meet their study objectives; and iii) Creation of a special methodology: In some cases, researchers may be motivated to create a unique LCA approach that has not yet been implemented in the software. Under such circumstances, they may have to create a special computational tool to match their study goals

The LCA software selection depends on the research objectives, equipment acquisition costs, the data held, and program usage (Manco *et al.*, 2023; Petrillo *et al.*, 2022). LCA software is also often used in the implementation of environmental management systems as it has many benefits beyond environmental impact analysis, such as economic analysis, weak-point assistance, opportunities for improvement at a stage that has a high impact, and opportunities to replace cheaper or environmentally friendly fuels (Deepak *et al.*, 2022). Therefore, the LCA method could accurately identify stages with poor impact and performance. Moreover, the LCA method provides decision-makers with a tool for making complex choices and providing relevant and accountable information for reporting (Torkayesh *et al.*, 2022). By providing actual data and scientific analyses regarding the impact of agricultural waste management environmental systems, LCA ensures that each approach is evidence-based and sustainable. The LCA method can also help decision-makers contribute to reducing economic impacts and developing an effective waste management system so that an environmental management system can be developed

Impact categories selection

The selection of impact categories is one of the objectives for determining whether the selected application is in accordance with the desired target; however, if the impact category analyzed is broader, it will provide a more detailed analysis to achieve a sustainable system (Khanali *et al.*, 2022). Fig. 7 shows the number of impact categories most often used to meet technology goals. The Global Warming Potential (GWP) impact category is used most commonly, at 80–94%, because it covers climate change issues and is required to consider potential environmental implications. This is in line with the research by Pratibha *et al.* (2019), where the main indicators of sustainability cover technologies with low GHG emissions were classified as GWP. In the context of GWP, key stages in the life cycle contributing to GWP, such as raw material extraction, production, transportation, use, and end-of-life disposal, should be identified to reduce GWP. When these are met, the potential trade-offs between environmental impacts will help decision-making for more sustainable alternatives. Therefore, evaluating the reduction in methane emissions caused by the breakdown of agricultural waste can be reduced when suitable management techniques, such as composting or anaerobic digestion, are used. Furthermore, the second impact analysis is the potential for human toxicity and ozone depletion of 30-45%, while the analysis of other impacts such as social, economic, ozone depletion, and photochemical ozone formation. An LCA can reveal the type and amount of toxic substances released during the life cycle of a product. These findings highlight the life cycle stages that contribute significantly to the impact of toxicity in humans. For example, the use of pesticides or other chemicals in agriculture may contribute to human toxicity, highlighting the importance of sustainable practices and using alternative ingredients. Moreover, ozone depletion in a city reveals the extent to which a product or process contributes to ozone layer depletion, highlighting certain substances or

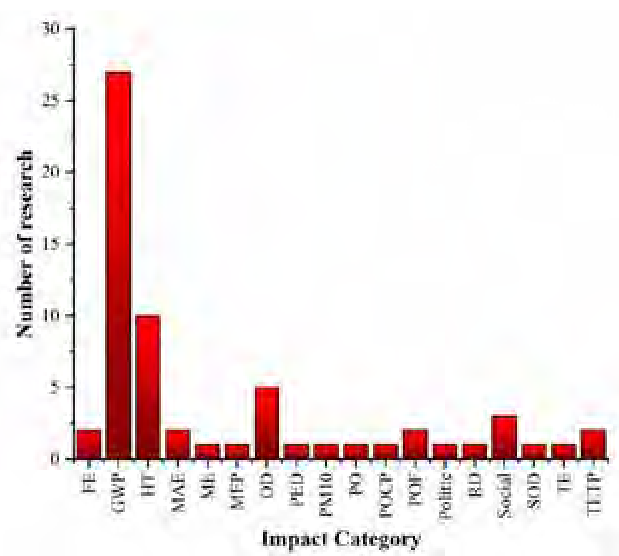

Fig. 7: Impact category analysis

manufacturing processes with high ozone depletion potential. Sustainable alternatives that minimize or eliminate the use of ozone-depleting substances can be identified, thereby contributing to more environmentally friendly practices. Sustainability outcomes depend on the balance between various environmental impacts. For example, a product or process may have a lower ozone depletion potential but a higher toxicity in humans, or vice versa. LCA should consider these trade-offs and help identify strategies to minimize negative impacts while maximizing positive ones. Agricultural waste management significantly affects climate change, resource depletion, and ecosystem health. Burning agricultural residues or neglecting trash may release methane and exacerbate global warming. When agricultural waste is not recycled, soil erosion and synthetic fertilizer use deplete resources (Khanali *et al.*, 2022). This method reduces soil fertility and agricultural production. Water contamination and habitat degradation due to improper waste management threaten ecosystem health (McAuliffe *et al.*, 2020). Sustainable waste management, such as composting and anaerobic digestion, is beneficial. Renewable energy from waste biogas reduces gas emissions from glasshouses. Recycling agricultural waste improves soil organic matter, lowers synthetic fertilizer use, and supports sustainable farming. The rest of the analysis, which is rarely used, can potentially help further studies to suggest substituting materials, raw materials, fuels, and the development of tools for managing agricultural waste to achieve a sustainable solution (Budihardjo *et al.*, 2023b). This is because, when measuring the total energy used in each life cycle of the technology used, high energy use can significantly impact natural resources and GHG emissions.

Furthermore, for the economic sector, such cost cuts are expected by analyzing potential cost savings from effectively managing agricultural waste, considering opportunities for waste-based goods, and decreasing disposal costs (Chepeliev *et al.*, 2022). Resource recovery evaluates the financial value of materials recovered from trash, such as compost, that can be used to produce bioenergy or improve soil (Haque *et al.*, 2023). Market development, which measures the market expansion of waste-derived goods, stimulates economic opportunities in the agricultural waste management sector followed by health and safety (D’Agaro *et al.*, 2022). Analyzing how well waste management decreases health risks for farmers, employees, and people in the area by minimizing exposure to dangerous substances is required (Mehmood *et al.*, 2022). This sector is also covered by community engagement, which assesses the potential to create new employment opportunities and generate income through waste management practices and value-added products by examining local community involvement and awareness of waste management initiatives, encouraging a sense of responsibility and ownership and improving livelihoods. Support for conformity with laws and regulations is required for systematic application, and legal compliance assesses how well agricultural waste management operations adhere to current waste and environmental rules and whether policies are well-aligned. It also analyzes how national and international policies, such as pledges to the environment and sustainable development goals, connect with waste management initiatives. By considering these impact categories, stakeholders may build thorough plans for efficient agricultural waste management that address environmental, economic, and social concerns while fostering sustainability and resilience in agriculture.

Key sensitives parameters

Sensitivity analysis is used to determine how various characteristics or variables affect the results of agricultural waste management. This section discusses agricultural waste management and its effects on environmental, economic, and social issues. However, these studies typically include additional criteria (Awasthi *et al.,* 2022). The amount of agricultural waste produced substantially impacts the total waste management plan, and some studies indicate a waste generation rate of 30–55%, as this is a widespread issue (Karić *et al.,* 2022). The scalability of the waste management system can be evaluated, and the critical point at which alternative waste treatment methods are required can be identified by analyzing the sensitivity to changes in the rate of waste formation (Sabet *et al.,* 2023). Agrochemical containers, crop residues, animal dung, and other waste products are produced by diverse agricultural activities in addition to the composition of agricultural waste. The most important waste streams can be identified by analyzing their sensitivity to changes in waste composition, and their management can then be based on the potential for resource recovery and environmental impact (Ganesan and Valderrama, 2022). Additionally, selecting from a range of processing technologies, such as anaerobic digestion, incineration, composting, and other cutting-edge technologies, as shown in Fig. 8 is the most widely discussed topic. The compatibility of these technologies in multiple situations can be determined using sensitivity analysis, which considers energy efficiency, GHG emissions, nutrient recovery, and economic viability (Zoppi *et al.,* 2023). Sensitivity analysis can evaluate the impact of changes in the market prices of agricultural and waste-derived products (such as bioenergy and biological fertilizers), which is another factor that is rarely considered (Bhatt *et al.,* 2023). This analysis can determine prospective revenue sources and impact the economic viability of waste management solutions. Government laws and regulations can significantly impact how agricultural waste is managed; however, there is a lack of sensitivity analysis. Different policy scenarios, such as financial incentives for garbage recycling or fines for improper waste disposal, can be designed using sensitivity analysis to determine their impact on waste management decisions (Ma *et al.,* 2023). The last and most debated component is social acceptance, which overlaps with existing conditions, the workplace, and stakeholders' willingness to engage. Sensitivity analysis can help with the adoption of sustainable waste management, which can be influenced by public perception and engagement.

Important sensitive criteria for agricultural waste management

Identifying and prioritizing sensitive criteria are essential in agricultural waste management to ensure efficient and long-lasting waste treatment procedures. These criteria are crucial because they significantly impact the development of waste management methods. The following are some delicate factors for managing agricultural waste, listed in order of importance: i) Waste Composition: It is crucial to comprehend the makeup of agricultural waste. The viability and efficacy of various waste management strategies can be affected by variations in nutrient content, moisture levels, and the ratio of organic to inorganic elements; ii) Resource Recovery Potential: It is important to evaluate the possibility of recovering resources and energy from agricultural waste. Technologies that effectively transform trash into useful goods, such as compost for soil improvement or biogas from anaerobic digestion, are widely desired; iii) Environmental impacts: The effects of agricultural waste management systems on the environment should be carefully considered. Minimizing emissions, reducing GHG emissions, and avoiding soil and water pollution are important factors to consider when choosing the best waste management techniques; iv) It is important to consider the applicability, compatibility, and ability of the technology to handle particular forms of agricultural waste. To achieve the best outcomes, the technology should be chosen considering the waste composition and regional context; v)

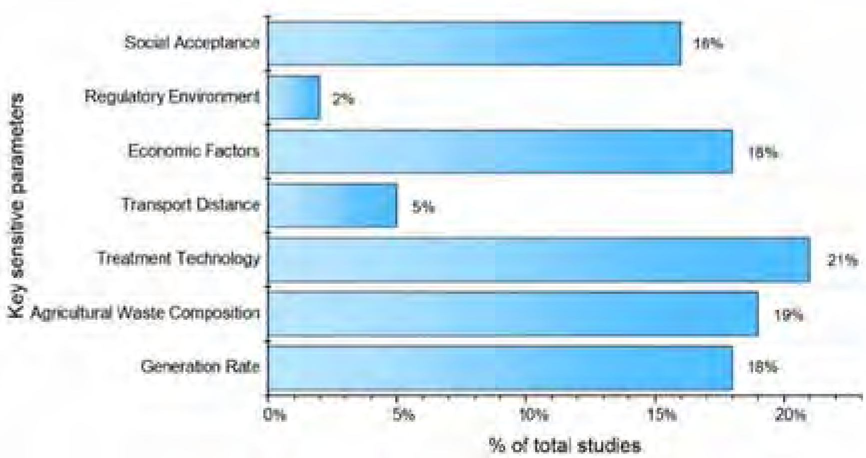

Fig. 8. Key sensitive parameters, sensitivity analysis has been used in research to identify and completely detail critical sensitive parameters that have a major impact on the outcomes

Economic Viability: Agricultural waste management strategies must be economically viable. The long-term sustainability of waste management projects is significantly influenced by their cost-effectiveness and potential for resource recovery to generate income; vi) Local Context and Socioeconomic Factors: Successful implementation and community involvement in waste management programs depends on taking into account the local context, involving social acceptance, existing infrastructure, and economic conditions; vii) Energy Restoration: To maximize the advantages of energy generation, the efficiency of energy recovery systems such as biogas yield from anaerobic digestion should be adequately analyzed; viii) Market Demand and Supply: A successful circular economy must consider the supply and demand dynamics of items made from recycled agricultural waste. Compost, biochar, or other recycled goods are used properly when viable markets are identified; ix) Transportation distance: Reducing travel distances between waste-generation sites and management facilities lowers carbon emissions and transportation expenses; x) Life Cycle Assessment: Carrying out a thorough LCA enables a holistic assessment of the environmental effects linked to various waste management solutions, facilitating well-informed decision-making. Agricultural waste management strategies can be created and implemented to maximize resource recovery and environmental consequences and fit with each region's distinctive characteristics by prioritizing these delicate criteria and considering how they interact.

Guideline best practices for recycle agricultural waste management

The best handbook for managing agricultural waste offers a thorough overview of important factors that must be considered (Bureau and Antón, 2022). It addresses several crucial topics, such as waste classification, resource recovery, sustainability, public awareness, and regulatory considerations (Tseng *et al.*, 2022). Although the recommendations contain insightful advice, several areas should be strengthened and elaborated, and the type and volume of agricultural waste produced on agricultural land must be carefully evaluated (Budihardjo *et al.*, 2023a). This process aids in identifying waste-management issues and growth prospects. Subsequently, waste stream characteristics were grouped according to their composition, biodegradability, and possibility of recycling or reuse. The stage of "Reduce and Prevent Waste Generation" needs to be given more attention because it can motivate farmers to use precision farming methods to maximize resource use and decrease overproduction, which then results in reduced waste production (Starek-Wójcicka *et al.*, 2022). It can also encourage the implementation of effective irrigation techniques, pest control strategies, and nutrition management strategies to reduce agricultural by-products (Tedesco *et al.*, 2023). If the phases cannot be shortened owing to strong demand, another option is to reduce waste in the livestock industry by encouraging people to compost organic waste products, such as agricultural residues, manure, and kitchen scraps, to produce nutrient-rich soil amendments. Encouraging farmers to use a zero-waste strategy, such as recycling agricultural packaging or switching to bioenergy generation from waste, is necessary. To support this, it is necessary to dispose of trash responsibly (Qin *et al.*, 2022). Agricultural waste should not be burned in an open environment as it releases dangerous air pollutants. Promoting controlled combustion or looking into different disposal options, such as anaerobic digestion is required. To avoid pollution, one must ensure that the waste disposal sites are far from vulnerable ecosystems and water bodies (Pantusa *et al.*, 2023). Recycling and resource recovery, which promote the recycling and reuse of agricultural waste, such as converting crop residues into animal feed or biofuel production, and exploring the potential to create value-added products from agricultural by-products, such as biodegradable packaging materials or natural fertilizers, continue to implement sustainable concepts (Koul *et al.*, 2022; Kumar Sarangi *et al.*, 2023). Collaboration and education are necessary for executing sustainable ideas. Cooperation should be encouraged among farmers, scientists, government organizations, and waste management professionals to create better approaches for managing agricultural waste (Farooq *et al.*, 2022). Additionally, it is necessary to conduct workshops, training sessions, and awareness campaigns to inform farmers about the significance of sustainable waste management techniques. Compliance with the regulations is required for their application. Ensuring that all agricultural waste management techniques adhere to applicable local, regional, and federal laws

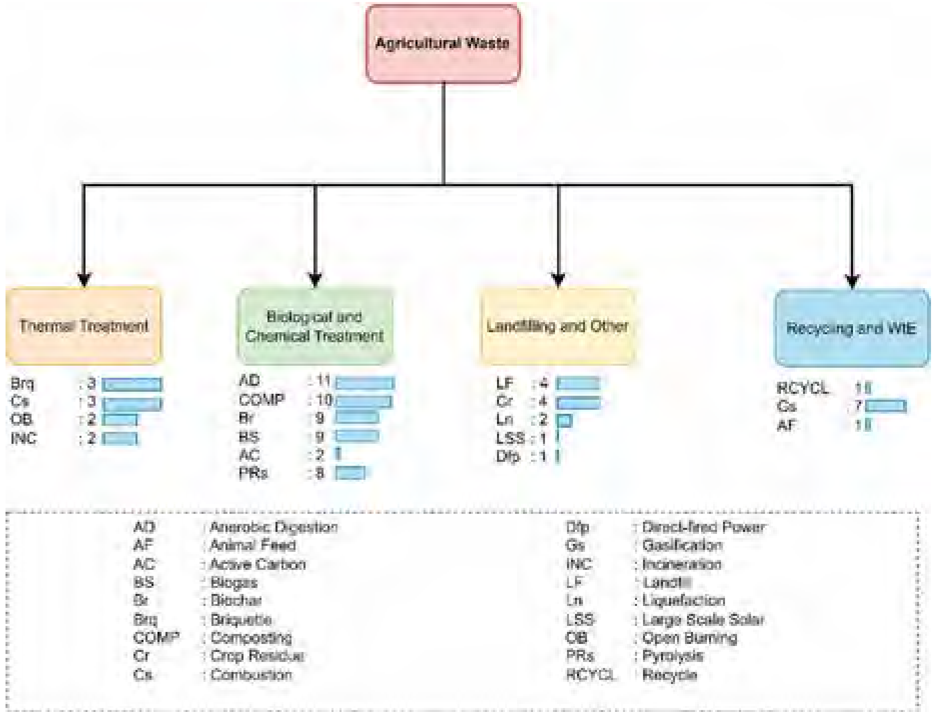

Fig. 9: Types and quantities of agricultural treatment technologies under evaluation

and regulations is necessary (Hemidat *et al.*, 2022). Farmers should be encouraged to adopt effective waste management practices by adhering to any changes in waste management regulations. Finally, monitoring and assessments are required to ensure that this concept is feasible. Installing mechanisms to monitor waste production and disposal methods can help with the success of waste management plans. Regularly evaluating the effects of waste management projects on agricultural productivity, environmental safety, and long-term economic viability is important. Agricultural waste management is a crucial component of sustainable agriculture. As per these recommendations, farmers can effectively manage their waste, reduce their adverse environmental effects, and convert it into useful resources. Adopting effective agricultural waste management methods benefits individual farms and helps develop a robust and environmentally conscious agricultural industry.

Reviewed technology

The existing conditions and advanced technologies have diversified the technologies used for agricultural waste management. The various types of technologies and quantities frequently used in these studies are shown in Fig. 9. Various methods that have been developed and implemented for agricultural waste have changed significantly from landfilling methods to becoming energy sources, such as biochar, biogas, briquettes, and various methods that produce energy, such as solar and electricity. However, several methods lack technology, such as animal feed. Many methods still use thermal scenarios such as gasification, pyrolysis, and combustion. Overall, these results have a variety of methods with various approaches, from traditional to advanced, which are analyzed by LCA experts to assess potential environmental impacts.

Suggested agricultural waste management technologies/facilities

This section summarizes the various methods for managing traditional and advanced agricultural waste in Asia, as shown in Figs. 10 and 11, apart from those analyzed, because they do not meet the criteria. Asia has many traditional practices because

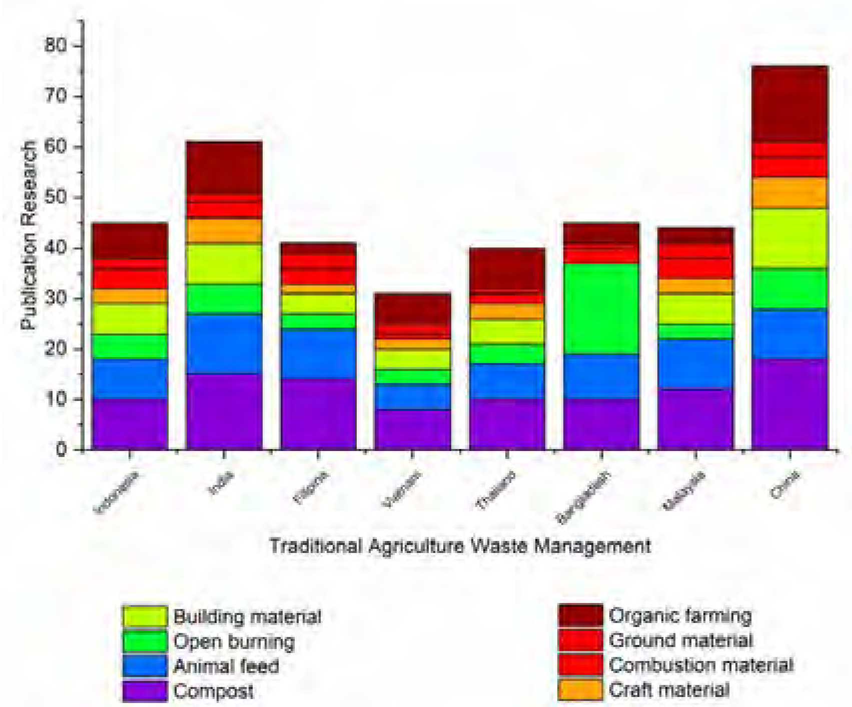

Fig. 10: Traditional agricultural waste management

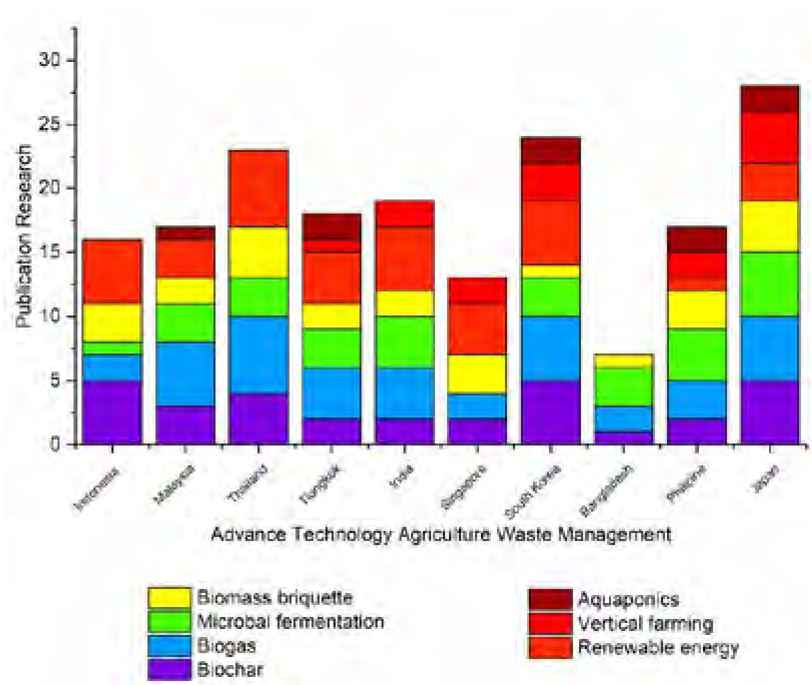

Fig. 11: Advance technology agriculture waste management

farmers often do not have access to resources, machinery, and contemporary technologies (Chaudhary *et al.*, 2023). Traditional farming techniques are usually more practical for small-scale farmers with limited resources because they are more accessible and affordable (Mizik, 2023). Traditional agricultural practices have changed over time to accommodate certain local factors, such as climate, soil type, and resource availability, which is another reason why many traditional methods are still in use (Chimi *et al.*, 2022; Samela *et al.*, 2022). These techniques frequently fit the particular needs and challenges of a region (Ezugwu *et al.*, 2022). Traditional agricultural methods are frequently taught and passed down from parents to younger generations in farming families or communities because of the lack of knowledge and skill transfer. This information transfer ensured the continuation of customary practices. There is also a connection between nature and sustainability, as traditional agriculture frequently emphasizes both concepts. By improving soil fertility, water conservation, and organic pest management, these techniques can support long-term ecological equilibrium (Vasseghian *et al.*, 2022). Moreover, cultural identity and food security have emerged. Local cuisine may be influenced by traditional crops and farming methods, which may be culturally important (Baldi *et al.*, 2022). Maintaining traditional agricultural practices helps preserve cultural identity and food security. Although traditional agricultural management has numerous advantages, it is crucial to understand how sustainable and current agricultural innovations can improve and supplement conventional approaches (Muhie, 2022). An integrated approach incorporating conventional knowledge with contemporary technologies is necessary to increase productivity, efficiency, and environmental sustainability in Asian agriculture (Kannan *et al.*, 2023). Governments, researchers, and organizations can play significant roles in assisting farmers in adopting sustainable and cutting-edge agriculture, while respecting and protecting traditional knowledge.

play a significant role in assisting farmers in adopting sustainable and cutting-edge agricultural.

Owing to several factors, such as the frequent need for considerable initial outlay and ongoing expenses, there are few advanced technologies in Asia. It may be difficult for small-scale farmers and rural populations across Asia, who constitute a significant portion of the agricultural sector, to afford this technology. Apart from technological matters, there is also the understanding that all agricultural waste will decompose by itself. The adoption process is impeded by upfront costs (Shaikh *et al.*, 2022). Lack of Awareness and Knowledge: Many farmers and other rural stakeholders may be unaware of the advantages of cutting-edge agricultural waste management systems (Fielke *et al.*, 2022). To persuade farmers with more expansive agricultural holdings to directly utilize crop waste, animal manure, and pruning materials instead of synthetic fertilizers, it is necessary to emphasize the advantageous outcomes regarding economics, the environment, and agriculture. On-farm organic resource utilization can substantially reduce input expenses for producers with larger farmland holdings. Alternatives to purchasing synthetic fertilizers that are frequently available on-site, sourced locally at reduced or non-existent expenses, and consist of crop refuse, animal manure, and pruning materials. In contrast to synthetic fertilizers, which may provide instantaneous nutrient availability but have the potential to deteriorate soil health gradually, organic materials impart long-term fertility to the soil through direct application. This method generates organic matter and ensures sustainable long-term productivity. Understanding how these technologies enhance waste management procedures is hampered by a lack of informational and educational resources. Technology and regional context adaptation: many cutting-edge waste management systems have been created outside Asia, and it may be difficult to adapt them to the particular requirements and conditions of Asian agricultural settings (Shokri and Fard, 2023). Although this can take time, localizing and modifying technology to meet regional demands is necessary. Cultural and traditional elements: the culture and heritage of many Asian communities are firmly rooted in traditional agricultural methods. Traditional approaches may have to be abandoned when a new technology is implemented, leading to resistance or skepticism. Furthermore, it is known that organic waste, including agricultural waste, naturally decomposes; however, recycling amplifies this organic process and derives multiple benefits from the waste. Composting is a prevalent recycling technique that involves the intentional decomposition of organic agricultural waste in a controlled environment, generating a nutrient-dense compost that functions exceptionally well as an organic fertilizer. Compost enhances soil structure, optimizes water retention, and supplies vital nutrients to plants, thereby improving soil fertility and the overall health of crops. Implementing anaerobic digestion and composting as methods for recycling agricultural waste contributes to mitigating glasshouse gas emissions that would otherwise accumulate in landfills during natural decomposition. Methane, a highly potent glasshouse gas, is produced under landfill-like anaerobic conditions. Diverting organic waste from landfills by recycling reduces emissions and alleviates the adverse effects of climate change. Furthermore, agricultural waste recycling promotes sustainable agricultural practices by mitigating environmental impacts, reducing dependence on synthetic fertilizers, and enhancing soil health, enhancing the productivity and long-term resilience of agricultural systems. Governments, research institutes, the commercial sector, and non-governmental organizations must collaborate to address this challenge. Accelerating the adoption of cutting-edge technology for agricultural waste management in Asian nations would require stimulating public-private partnerships, developing awareness campaigns, offering financial support, and promoting information exchange (Kountios *et al.*, 2023). By removing these obstacles and encouraging environmentally friendly technologies, Asian countries can utilize cutting-edge waste management techniques to build a more resilient and sustainable agricultural industry (Iwuozor *et al.*, 2022). Effective agricultural waste management is essential for resource conservation, environmental preservation, and sustainable farming (Kharola *et al.*, 2022). The most effective technologies and facilities for managing agricultural waste emphasize resource efficiency, environmental sustainability, and a circular economy (Onyeaka *et al.*, 2023). Farmers and waste management stakeholders can dramatically reduce waste, produce renewable energy, increase soil fertility, and contribute to a more sustainable and robust agricultural sector using these technologies. Fostering cooperation among the public, corporate, and academic sectors can also promote innovation and the adoption of cutting-edge waste management techniques. Implementing a waste management system that integrates several waste processing methods, such as recycling, composting, biochar, and biogas production from anaerobic digestion, is necessary. By incorporating recycling, composting, biogas production from anaerobic digestion, and biochar production, an integrated approach to agricultural waste management was established, focusing on establishing a circular and sustainable system within the agricultural domain. Recycling entails repurposing by-products, including animal manure and crop residues, thereby decreasing dependence on external inputs and minimizing the environmental impact. Composting transforms organic waste into compost abundant in nutrients, thereby completing the nutrient cycle and improving the overall health of the soil. Biochar production is achieved by pyrolyzing organic materials, enhancing nutrient availability, water retention, and soil quality, thereby contributing to sustainable agriculture. Concurrently, biogas generation through anaerobic digestion serves the dual purpose of organic waste treatment and renewable energy provision for on-farm utilization, thereby adhering to the tenets of self-reliance and a diminished ecological footprint. The aforementioned integrated approach prioritizes waste valorization, establishment of closed nutrient cycles, and a holistic strategy that tackles the dual challenges of waste disposal and resource efficiency in the agricultural system. Using a biotechnological process called anaerobic digestion, organic wastes such as agricultural residues, animal manure, and food scraps are transformed into digestate and nutrient-rich biogas (Manikandan *et al.*, 2023). Although the digestate can be used as a natural fertilizer, biogas can also be used to generate heat and electricity from renewable sources. Anaerobic digestion is an eco-friendly method of waste management because it reduces waste volume and GHG emissions, with studies showing a net saving in GWP emissions of −31.6 kg CO_2 (Budihardjo *et al.*, 2023b). Composting is the second approach that is widely utilized and sustainable and has an impact of less than -2900 kg CO2 eq/t when combined with anaerobic digestion (Li *et al.,* 2018). Composting is a biological process that converts organic waste into nutrient-rich humus. Composting facilities make it easier for agricultural waste to decompose under controlled conditions and produce high-quality compost (Badawi, 2023). Compost can be used to improve soil quality, retain water, and increase nutritional content. Compost is produced effectively and safely owing to large-scale composting facilities. Biomass and bioenergy crops, which use agricultural waste, such as crop residues and wood chips, as raw materials for bioenergy production, are widely used in the cited research (Rashedi *et al.*, 2022). Biomass waste is transformed into biofuels, such as bioethanol or bio-oil, and syngas by gasification or pyrolysis. Biofuels have the potential to replace fossil fuels, reduce GHG emissions, and support a circular economy (Kovacs *et al.*, 2022). Biochar manufacturing facilities employ pyrolysis to create biochar, a stable form of carbon, from agricultural waste. Mohammadi *et al.* (2017) showed little environmental impact in reducing the carbon footprint of spring and summer rice by 26% and 14%, respectively. Biochar is a soil additive that improves soil fertility, water retention, and nutrient availability. Additionally, long-term carbon sequestration in the soil helps slow climate change. Plants process agricultural waste and other types of garbage, transforming it into energy, often electricity and heat, using the waste-to-energy (WTE) strategy (Rani *et al.*, 2023). Modern WTE techniques, such as incineration with energy recovery, guarantee the effective and safe disposal of trash while also capturing energy from the burning process and having less impact on the environment with a GWP of −5 kg CO_2 eq/t (Tong *et al.*, 2018; Priyambada *et al.*, 2023). Recycling facilities for agricultural waste focus on removing and processing recyclable components from waste streams such as plastics, metals, and paper. Additionally, recycling facilities are looking into novel ways to transform agricultural waste into value-added goods, such as composite materials or biodegradable packaging (Mujtaba *et al.*, 2023). However, many technologies will be ineffective without integrated farming systems that employ a comprehensive approach to waste management and use agricultural waste on-site to promote soil health, boost livestock feed, and produce renewable energy. For instance, animal excrement can be nutrient-rich, and plant residues can be used as animal feed. Decentralized waste management is required to support various approaches and the ensuing environmental effects. Waste management systems promote waste processing at the farm or local level. This approach lowers the cost of transportation, shortens the distances across which waste must be transported, and makes it easier to recycle and reuse the waste locally. Finally, smart technologies such as sensors and the Internet of Things (IoT) should be adopted for effective waste management. These technologies can be incorporated into waste management systems for waste collection, monitoring of composting or anaerobic digestion processes, and ensuring effective resource use. Minimizing agricultural waste at source is imperative for fostering sustainable and resource-efficient farming practices. Farmers can optimize inputs, such as water, fertilizers, and pesticides, by utilizing precision farming technologies, including sensors and GPS-guided equipment, thereby mitigating the risk of environmental damage and over-application. Incorporating biological control methods such as Integrated Pest Management (IPM) practices reduces the dependence on chemical pesticides, thereby decreasing the environmental impact of agriculture. Diversification and crop rotation disrupt the cycle of pests and diseases, improve soil fertility, and reduce the need for excessive chemical inputs. By optimizing harvesting practices, including selective and opportune harvesting, the risk of postharvest spoilage and over-ripening-related losses is reduced to that of mature and healthy harvested crops. Furthermore, implementing cold chain management for perishable produce, establishing adequate storage facilities, and investigating on-farm processing alternatives all contribute to the reduction of postharvest waste.

Gaps and critical findings in implementation

A useful approach for assessing the environmental effects of agricultural waste management systems and facilities is LCA. Although LCA has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be challenging to gather complete and accurate data for the entire lifecycle of agricultural waste management technology. Information gaps exist in areas such as trash collection, transportation, treatment, and disposal. The LCA findings may be inaccurate because of missing or conflicting data. Agricultural practices differ significantly based on geography, crop type, and management strategies. This variability must be considered in LCA studies of agricultural waste management to reflect the environmental effects of various waste management solutions appropriately. Limited Attention to Secondary Effects: The direct environmental effects of waste management are frequently the focus of LCA studies, but they may overlook secondary effects such as indirect land-use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis. The impact assessment approach is the final step, frequently leading to gaps. In LCA, picking an appropriate impact assessment methodology is crucial for an LCA. To achieve consistency and comparability among studies, designing specialized impact assessment procedures for agricultural waste management is necessary. In LCA studies emphasizing the significance of source segregation and pretreatment of agricultural wastes, separating sources and pretreatment has been one of the criteria for a crucial comparison. The quality of recycled materials or energy recovered from trash can be improved through proper source segregation, which enables more effective waste management procedures. The possibilities of energy recovery are as follows: Anaerobic digestion, biochar, and pyrolysis are the most common agricultural waste management techniques and have shown substantial promise for energy recovery through LCA. Using this technology, farms can generate biogas, charcoal, or bioenergy that can be used on-site or fed into a grid. Recycling nutrients and improving soil quality: Agricultural waste can be recycled back into the soil as organic amendments, boosting soil fertility and lowering the demand for fertilizers. Examples of such wastes include crop residue and animal manure. The relevance of nutrient recycling and its beneficial effects on soil health have been emphasized in LCA studies, but this has not been covered in depth in the aforementioned research. To achieve sustainability, a circular economic strategy to manage agricultural waste can result in more sustainable procedures. LCA studies have shown the possibility of reducing overall environmental effects and resource consumption by reusing and recycling waste materials. To promote sustainable waste management and aid in the transition to a more resource- and environment-friendly agricultural sector, it is important to fill the identified gaps and consider the major findings of the LCA study for agricultural waste management.

RECOMMENDATION

Asian nations can address the issues with managing agricultural waste while creating a more resilient and sustainable agriculture industry by incorporating interactive and sustainable solutions. Governments, communities, and other stakeholders must work together if they are to manage agricultural waste appropriately over the long term. Encourage farmers, local communities, researchers, and policymakers to work together actively to discover regionally unique problems with agricultural waste management and create specialized solutions. Participation from the community encourages a sense of responsibility, which results in more efficient and sustainable waste management techniques. Invest in programs that develop the capacity of waste management stakeholders and educate farmers about sustainable waste management techniques. Training sessions may concentrate on appropriate waste segregation, composting methods, anaerobic digestion, and other cutting-edge agricultural technologies appropriate for Asia. Implementing an integrated waste management system that includes recycling, composting, biochar, and anaerobic digestion biogas production. Recycle, compost, biogas from anaerobic digestion, and biochar synthesis create an integrated approach to agricultural waste management that promotes a circular and sustainable system. By recycling byproducts like animal manure and crop leftovers, dependence on external inputs and environmental effect are reduced. Making nutrient-rich compost from organic waste completes the nutrient cycle and improves soil health. Pyrolyzing organic materials produces biochar, which improves soil quality, water retention, and nutrient availability for sustainable agriculture. Self-reliance and reduced environmental impact are achieved by generating biogas from anaerobic digestion of organic waste and providing renewable energy for on-farm use. The integrated method prioritizes waste valorization, closed nutrient cycles, and a holistic approach to agricultural waste management and resource efficiency. The holistic approach guarantees effective management of various waste streams and maximizes resource recovery. Promoting the use of biogas production methods that generate the fuel from agricultural waste, such as plant leftovers and animal dung. A renewable energy source for rural communities, biogas can be electricity, heating, and cooking. Promotes on-farm composting and composting of agricultural waste as a natural, inexpensive way to recycle organic matter. Vermicomposting and Composting. As a result, the soil is more fertile, fewer chemical fertilizers are needed, and fewer greenhouse gas emissions are produced. To encourage farmers and waste management facilities to adopt sustainable practices, offer financial incentives and policy support. Environmentally friendly waste management systems can be adopted more quickly if the government offers subsidies, tax breaks, and favorable legislation. Can encourage the successful implementation of waste management practices by facilitating technology transfer and knowledge sharing across Asian nations. The adoption of sustainable solutions can be accelerated by regional cooperation. The circular economy's concepts should also be included into strategies for managing agricultural waste, with a focus on waste reduction, reuse, and recycling. Encouraging the creation of agricultural waste-derived value-added goods including biochar, bio-based materials, and biodegradable packaging. Spend money on research and development to create and enhance agricultural waste management methods. Accept cutting-edge waste-to-energy techniques, intelligent waste collection systems, and other developing technology. The importance of sustainable agricultural waste management and its benefits for the environment, human health, and rural livelihoods should be made more widely known. Campaigns for proper waste management can be promoted through education and behavior change.

CONCLUSION

Life cycle thinking has emerged as an innovative and comprehensive viewpoint that considers the entire recycling process to evaluate the potential and true implications of agricultural waste recycling. The core idea of "sustainable" is life cycle thinking, an original and comprehensive strategy that goes beyond conventional linear evaluations. This study demonstrated the significance of context-specific techniques in recycling agricultural waste. Adapting waste management solutions to local conditions and resource availability is essential because agricultural practices vary between locations. Identifying and prioritizing sensitive criteria are essential when choosing agricultural waste management to ensure efficient and long-lasting waste treatment procedures. Various methods developed and implemented for agricultural waste have changed significantly from landfilling methods to becoming energy sources, such as biochar, biogas, briquettes, and various methods that produce energy, such as solar and electricity. This review provides insights into how recycling agricultural waste can dramatically lower GHG emissions, conserve resources, and improve soil fertility. Composting, anaerobic digestion, and pyrolysis are used to create biochar, a waste recycling method that holds promise for sustainable waste management. In addition to efficiently managing agricultural waste, these technologies help generate electricity and sequester carbon, thereby advancing the objectives of climate change mitigation and circular economy. Widespread adoption of sustainable waste management techniques can be facilitated by integrating community involvement, capacity building, and policy assistance, allowing farmers and local communities to participate actively. Environmentally friendly waste management systems can be adopted more quickly if the government offers subsidies, tax breaks, and favorable legislation. This can encourage the successful implementation of waste management practices by facilitating technology transfer and knowledge sharing across Asian nations. Regional cooperation can accelerate the adoption of sustainable solutions. Although LCA has been used to analyze several waste management strategies, including those specific to agricultural waste, certain significant gaps and discoveries still require attention for a more thorough analysis. It might be difficult to gather complete and accurate data for the entire lifecycle of agricultural waste management technology. Limited Attention to Secondary Effects: The direct environmental effects of waste management are frequently the focus of LCA studies, but they may overlook secondary effects such as indirect land-use change, habitat damage, and biodiversity effects. It is crucial to consider these secondary effects in a more comprehensive analysis. To promote sustainable waste management and aid in the transition to a more resource- and environment-friendly agricultural sector, it is important to fill the gaps that have been identified and consider the major findings of the LCA study for agricultural waste management.

AUTHOR CONTRIBUTIONS

S. Sumiyati is responsible for making whole concept. B.P Samadikun is responsible for finding out the outline of each manuscript analyzed in managing agricultural waste, determining searches, compiling concepts, reviewing all manuscripts. A. Widiyanti is responsible for finding out the outline of each manuscript analyzed in managing agricultural waste, determining searches, compiling concepts, reviewing all manuscripts. S. Al Qadar reviewed the final report. A.S. Puspita is responsible for preparing drafts, journal analysis sources and reviewing the entire manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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ABBREVIATIONS

%	*Per cent*
AC	*Active carbom*
AD	*Anaerobic digestion*
Adp	*Abiotic depletion*
AF	*Animal Feed*
AP	*Acidification potential*
Br	*Biochar*
Brq	*Briquette*
Bs	*Biogas*
CF	*Carbon footprint*
COMP	*Composting*
Cr	*Crop residue*
Cs	*Combustion*
Dfp	*Direct-fired power*
DRPM	*Directorate of Research, Technology and Community Service*
DIKTI	*Directorate General of Higher Education, Research and Technology*
Ds	*Digestate*
Ect	*Ecotoxicity*
EP	*Eutrophication potential*
FD	*Fossil depletion*
FE	*Freshwater eutrophication*
FW	*Food waste*
GHG	*Greenhouse gasses*
Gs	*Gasification*
GWP	*Global warming potential*
HT	*Human toxicity*
INC	*Incineration*
IPM	*Integrated pest management*
KEMENDIKBUD	*Ministry of Education, Culture, Research, and Technology*

kg CO_2	kilogram of carbon dioxide
kg CO_2 eq/t	kilogram of carbon dioxide equivalent per ton
IoT	Internet of Things
LBP	*Large biogas scale production*
LCA	*Life cycle assessment*
LF	*Landfill*
Ln	*Liquefaction*
LSS	*Large scale solar*
MAE	*Marine Aquatic Ecotoxicity*
MEP	*Marine eutrophication potential*
Mt	*Metric ton*
OB	*Open burning*
OD	*Ozone Depletion*
pm10	*Particulate matter 10nm*
PO	*photochemical oxidation*
POCP	*Photochemical ozone creation potential*
POF	*Photochemical ozone formation*
PRISMA	*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*
PRs	*Pyrolysis*
RCYCL	*Recycle*
RD	*Resource depletion*
SOD	*Stratospheric ozone depletion*
TE	*Terrestrial ecotoxicity*
TETP	*Terrestrial ecotoxicity potential*

REFERENCES

Abbasi, R.; Martinez, P.; Ahmad, R., (2022). The digitization of agricultural industry–a systematic
literature review on agriculture 4.0. Smart Agric. Technol., 100042: 1-24 **(24 Pages)**.

Aberilla, J.M.; Gallego-Schmid, A.; Azapagic, A., (2019). Environmental sustainability of small-scale biomass power technologies for agricultural communities in developing countries. Renewable Energy. 141: 493-506 **(14 Pages)**.

Adekomaya, O.; Majozi, T., (2022). Promoting natural cycle and environmental resilience: A pathway toward sustainable development. S. Afr. J. Chem. Eng., 42: 229-240 **(12 Pages)**.

Ahmed, F.; Hasan, S.; Rana, M.; Sharmin, N., (2023). A conceptual framework for zero waste management in Bangladesh. Int. J. Environ. Sci. Technol., 20(2): 1887-1904 **(18 Pages)**.

Al-Rumaihi, A.; McKay, G.; Mackey, H.R.; Al-Ansari, T., (2020). Environmental impact assessment of food waste management using two composting techniques. Sustainability. 12(4): 1-23 **(23 Pages)**.

Arena, N.; Lee, J.; Clift, R., (2016). Life Cycle Assessment of activated carbon production from coconut shells. J. Cleaner Prod., 125: 68-77 **(10 Pages)**.

Awasthi, M.K.; Sindhu, R.; Sirohi, R.; Kumar, V.; Ahluwalia, V.; Binod, P.; Juneja, A.; Kumar, D.; Yan, B.; Sarsaiya, S., (2022). Agricultural waste biorefinery development towards circular bioeconomy. Renewable Sustainable Energy Rev., 112122: 1-17 **(17 Pages)**.

Badawi, M.A., (2023). Composting farm waste for production of high quality organic fertilizers and sustainable development. Integrated Waste Management: The Circular Economy, United Kingdom **(196 Pages)**.

Baldi, A.; Bruschi, P.; Campeggi, S.; Egea, T.; Rivera, D.; Obón, C.; Lenzi, A., (2022). The renaissance of wild food plants: Insights from Tuscany (Italy). Foods. 11(3): 1-28 **(28 Pages)**.

Bhatt, A.H.; Zhang, Y.; Milbrandt, A.; Newes, E.; Moriarty, K.; Klein, B.; Tao, L., (2023). Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. Energy Convers. Manage., 275: 1-16 **(16 Pages)**.

Blum, D., (2020). Ways to reduce restaurant industry food waste costsInt. J. Appl. Sci. Technol., 19(1): 1-12 **(12 Pages)**.

Bonilla-Alicea, R.J.; Fu, K., (2019). Systematic map of the social impact assessment field. Sustainability. 11(15): 1-30 **(30 Pages)**.

Budihardjo,M.A.; Huboyo, H.S.; Puspita, A.S.; Hutagaol, J.D.C., (2023a). Utilization of Bokashi Composting and Animal Feed Silage for Sustainable Agricultural Waste Management and Environmental Impact Analysis. Glob.Nest J., 25: 1-10 **(10 Pages)**.

Budihardjo, M.A.; Priyambada, I.B.; Chegenizadeh, A.; Al Qadar, S.; Puspita, A.S., (2023b). Environmental impact technology for life cycle assessment in municipal solid waste management. Global J. Environ. Sci. Manage., 9(SI): 145-172 **(28 Pages)**.

Bureau, J.C.; Antón, J., (2022). Agricultural Total factor productivity and the environment: A guide to emerging best practices in measurement. 1-42 **(42 Pages)**.

Chaudhary, A.; Timsina, P.; Karki, E.; Sharma, A.; Suri, B.; Sharma, R.; Brown, B., (2023). Contextual realities and poverty traps: why South Asian smallholder farmers negatively evaluate conservation agriculture. Renewable Agric. Food Syst., 38: 1-10 **(10 Pages)**.

Chen, B.; Chen, S., (2013). Life cycle assessment of coupling household biogas production to agricultural industry: A case study of biogas-linked persimmon cultivation and processing system. Energy Policy. 62: 707-716 **(10 Pages)**.

Chen, H.L.; Nath, T.K.; Chong, S.; Foo, V.; Gibbins, C.; Lechner, A.M., (2021). The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste. SN Appl. Sci., 3: 1-15 **(15 Pages)**.

Chen, S.; Chen, B.; Song, D., (2012). Life-cycle energy production and emissions mitigation by comprehensive biogas–digestate utilization. Bioresour. Technol., 114: 357-364 **(8 Pages)**.

Chepeliev, M.; Hertel, T.W.; van der Mensbrugghe, D., (2022). Cutting Russia's fossil fuel exports: Short-term pain for long-term gain. SSRN, 1-30 **(30 Pages)**.

Chimi, P.M.; Mala, W.A.; Fobane, J.L.; Essouma, F.M.; Mbom II, J.A.; Funwi, F.P.; Bell, J.M., (2022). Climate change perception and local adaptation of natural resource management in a farming community of Cameroon: A case study. Environ. Challenges. 100539: 1-10 **(10 Pages)**.

Clare, A.; Shackley, S.; Joseph, S.; Hammond, J.; Pan, G.; Bloom, A., (2015). Competing uses for China's straw: the economic and carbon abatement potential of biochar. Gcb Bioenergy. 7(6): 1272-1282 **(11 Pages)**.

Corominas, L.; Byrne, D.M.; Guest, J.S.; Hospido, A.; Roux, P.; Shaw, A., Short, M.D., (2020). The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. WaterRes., 184: 1-18 **(18 Pages)**.

D'Agaro, E.; Gibertoni, P.; Esposito, S., (2022). Recent trends and economic aspects in the rainbow trout (Oncorhynchus mykiss) sector. Appl. Sci., 12(17): 1-19 **(19 Pages)**.

Dahiya, S.; Katakojwala, R.; Ramakrishna, S.; Mohan, S.V., (2020). Biobased products and life cycle assessment in the context of circular economy and sustainability. Mater. Circ. Econ., 2: 1-28 **(28 Pages)**.

Dai, Y.; Zheng, H.; Jiang, Z.; Xing, B., (2020). Comparison of different crop residue-based technologies for their energy production and air pollutant emission. Sci. Total Environ., 136122: 1-10 **(10 Pages)**.

Deepak, A.; Sharma, V.; Kumar, D., (2022). Life cycle assessment of biomedical waste management for reduced environmental impacts. J. Cleaner Prod., 131376: 1-14 **(14 Pages)**.

Eyhorn, F.; Muller, A.; Reganold, J.P.; Frison, E.; Herren, H.R.; Luttikholt, L.; Mueller, A.; Sanders, J.; Scialabba, N.E.-H.; Seufert, V., (2019). Sustainability in global agriculture driven by organic farming. Nat. Sustainability. 2(4): 253-255 **(3 Pages)**.

Ezugwu, A.E.; Ikotun, A.M.; Oyelade, O.O.; Abualigah, L.; Agushaka, J.O.; Eke, C.I.; Akinyelu, A.A., (2022). A comprehensive survey of clustering algorithms: State-of-the-art machine learning applications, taxonomy, challenges, and future research prospects. Eng. Appl. Artif. Intell., 104743: 1-43 **(43 Pages)**.

Farooq, M.; Cheng, J.; Khan, N.U.; Saufi, R.A.; Kanwal, N.; Bazkiaei, H.A., (2022). Sustainable waste management companies with innovative smart Solutions: A Systematic Review and Conceptual Model. Sustainability. 14(20): 1-19 **(19 Pages)**.

Fielke, S.; Taylor, B.M.; Coggan, A.; Jakku, E.; Davis, A.M.; Thorburn, P.J.; Webster, A.J.; Smart, J.C., (2022). Understanding power, social capital and trust alongside near real-time water quality monitoring and technological development collaboration. J. Rural Stud., 92: 120-131 **(12 Pages)**.

Ganesan, K.; Valderrama, C., (2022). Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels. Energy. 123207: 1-13 **(13 Pages)**.

Gilani, H.R.; Ibrik, K.; Sanchez, D.L., (2023). Techno-economic and policy analysis of hydrogen and gasoline production from forest biomass, agricultural residues and municipal solid waste in C alifornia. Biofuels, Bioprod. Biorefin. 1-16 **(16 Pages)**.

Haga, K., (2021). Sustainable recycling of livestock wastes by composting and environmentally friendly control of wastewater and odors. J. Environ. Eng. Sci., 10: 163-178 **(16 Pages)**.

Haque, F.; Fan, C.; Lee, Y.-y., (2023). From waste to value: Addressing the relevance of waste recovery to agricultural sector in line with circular economy. J. Cleaner Prod., 137873: 1-12 **(12 pages)**.

Haumahu, S.A.Q.; Budihardjo, M.A.; Priyambada, I.B.; Puspita, A.S., (2023). Review of Household Waste Management Technology for a Greener Solution to Accomplish Circular Economy in Salatiga, Indonesia. Ecol. Eng. Environ. Technol., 9: 1-14 **(14 Pages)**.

Hauschild, M.Z.; Kara, S.; Røpke, I., (2020). Absolute sustainability: Challenges to life cycle engineering. CIRP Ann., 69(2): 533-553 **(21 Pages)**.

Hemidat, S.; Achouri, O.; El Fels, L.; Elagroudy, S.; Hafidi, M.; Chaouki, B.; Ahmed, M.; Hodgkinson, I.; Guo, J., (2022). Solid waste management in the context of a circular economy in the MENA region. Sustainability. 14(1): 1-24 **(24 Pages)**.

ISO 14040., (2006). Environmental management. Life cycle assessment principles and framework. International Standard International Organization for Standardization.

ISO 14044., (2006). Environmental management. Life cycle assessment requirements and guidlines. International Standard International Organization for Standardization.

Iwuozor, K.O.; Emenike, E.C.; Ighalo, J.O.; Eshiemogie, S.; Omuku, P.E.; Adeniyi, A.G., (2022). Valorization of sugar industry's by-products: a perspective. Sugar Tech., 24(4): 1052-1078 **(27 Pages).**

Kajtaz, M., (2019). Unconstrained shape optimisation of a lightweight side door reinforcing crossbar for passenger vehicles using a comparative evaluation method. Int. J. Automot. Technol., 20: 157-168 **(12 Pages)**.

Kannan, M.; Bojan, N.; Swaminathan, J.; Zicarelli, G.; Hemalatha, D.; Zhang, Y.; Ramesh, M., Faggio, C., (2023). Nanopesticides in agricultural pest management and their environmental risks: A review. Int. J. Environ. Sci. Technol., 20: 10507-10532 **(26 Pages)**.

Karić, N.; Maia, A.S.; Teodorović, A.; Atanasova, N.; Langergraber, G.; Crini, G.; Ribeiro, A.R.; Đolić, M., (2022). Bio-waste valorisation: Agricultural wastes as biosorbents for removal of (in) organic pollutants in wastewater treatment.

Chem. Eng. J. Adv., 100239: 1-17 **(17 Pages)**.

Kenett, R.S.; Zacks, S.; Gedeck, P., (2023). Industrial statistics: A computer-based approach with Python. Springer, Nature. 1-471 **(471 Pages)**.

Keng, Z.X.; Chong, S.; Ng, C.G.; Ridzuan, N.I.; Hanson, S.; Pan, G.-T.; Lau, P.L.; Supramaniam, C.V.; Singh, A.; Chin, C.F., (2020). Community-scale composting for food waste: A life-cycle assessment-supported case study. J. Cleaner Prod., 121220: 1-11 **(11 Pages)**.

Khanali, M.; Ghasemi-Mobtaker, H.; Varmazyar, H.; Mohammadkashi, N.; Chau, K.-w.; Nabavi-Pelesaraei, A., (2022). Applying novel eco-exergoenvironmental toxicity index to select the best irrigation system of sunflower production. Energy. 123822: 1-15 **(15 Pages)**.

Khandelwal, H.; Dhar, H.; Thalla, A.K.; Kumar, S., (2019). Application of life cycle assessment in municipal solid waste management: A worldwide critical review. J. Cleaner Prod., 209: 630-654 **(25 Pages)**.

Kharola, S.; Ram, M.; Mangla, S.K.; Goyal, N.; Nautiyal, O.; Pant, D.; Kazancoglu, Y., (2022). Exploring the green waste management problem in food supply chains: A circular economy context. J. Cleaner Prod., 131355: 1-14 **(14 Pages)**.

Koido, K.; Takeuchi, H.; Hasegawa, T., (2018). Life cycle environmental and economic analysis of regional-scale food-waste biogas production with digestate nutrient management for fig fertilisation. J. Cleaner Prod., 190: 552-562 **(11 Pages)**.

Koul, B.; Yakoob, M.; Shah, M.P., (2022). Agricultural waste management strategies for environmental sustainability. Environ. Res., 112285: 1-16 **(16 Pages)**.

Kountios, G.; Konstantinidis, C.; Antoniadis, I., (2023). Can the adoption of ICT and advisory services be considered as a tool of competitive advantage in agricultural holdings? A literature review. Agronomy, 13(2): 1-20 **(20 Pages)**.

Kovacs, E.; Hoaghia, M.-A.; Senila, L.; Scurtu, D.A.; Varaticeanu, C.; Roman, C.; Dumitras, D.E., (2022). Life cycle assessment of biofuels production processes in viticulture in the context of circular economy. Agronomy. 12(6): 1-15 **(15 Pages)**.

Kumar Sarangi, P.; Subudhi, S.; Bhatia, L.; Saha, K.; Mudgil, D.; Prasad Shadangi, K.; Srivastava, R.K.; Pattnaik, B.; Arya, R.K., (2023). Utilization of agricultural waste biomass and recycling toward circular bioeconomy. Environ. Sci. Pollut. Res., 30(4): 8526-8539 **(14 Pages)**.

Kurniawan, T.A.; Othman, M.H.D.; Hwang, G.H.; Gikas, P., (2022). Unlocking digital technologies for waste recycling in Industry 4.0 era: A transformation towards a digitalization-based circular economy in Indonesia. J. Cleaner Prod., 131911: 1-16 **(16 Pages)**.

Laurent, A.; Weidema, B.P.; Bare, J.; Liao, X.; Maia de Souza, D.; Pizzol, M.; Sala, S.; Schreiber, H.; Thonemann, N.; Verones, F., (2020). Methodological review and detailed guidance for the life cycle interpretation phase. J. Ind. Ecol., 24(5): 986-1003 **(18 Pages)**.

Lee, S.Y.; Sankaran, R.; Chew, K.W.; Tan, C.H.; Krishnamoorthy, R.; Chu, D.-T.; Show, P.-L., (2019). Waste to bioenergy: a review on the recent conversion technologies. BMC Energy. 1(1): 1-22 **(22 Pages)**.

Li, Y.; Manandhar, A.; Li, G.; Shah, A., (2018). Life cycle assessment of integrated solid state anaerobic digestion and composting for on-farm organic residues treatment. Waste Manage., 76: 294-305 **(12 Pages)**.

Llorach-Massana, P.; Cirrincione, L.; Sierra-Perez, J.; Scaccianoce, G.; La Gennusa, M.; Peña, J.; Rieradevall, J., (2023). Environmental assessment of a new building envelope material derived from urban agriculture wastes: the case of the tomato plants stems. Int J Life Cycle Assess., 28: 813-827 **(15 Pages)**.

Ma, H.; Li, M.; Tong, X.; Dong, P., (2023). Community-Level household waste disposal behavior simulation and visualization under multiple incentive policies—An agent-based modelling approach. Sustainability. 15(13): 1-15 **(15 Pages)**.

Manco, P.; Caterino, M.; Rinaldi, M.; Fera, M., (2023). Additive manufacturing in green supply chains: A parametric model for life cycle assessment and cost. Sustainable Prod. Consumption. 36: 463-478 **(16 Pages)**.

Manikandan, S.; Vickram, S.; Sirohi, R.; Subbaiya, R.; Krishnan, R.Y.; Karmegam, N.; Sumathijones, C.; Rajagopal, R.; Chang, S.W.; Ravindran, B., (2023). Critical review of biochemical pathways to transformation of waste and biomass into bioenergy. Bioresour. Technol., 128679: 1-20 **(20 Pages)**.

Marmiroli, B.; Rigamonti, L.; Brito-Parada, P.R., (2021). Life cycle assessment in mineral processing–a review of the role of flotation. Int J Life Cycle Assess., 27: 62-81 **(20 Pages)**.

Mazzi, A., 2020. Introduction. Life cycle thinking. in: Life cycle sustainability assessment for decision-making, Elsevier. 1-19 **(19 Pages)**.

McAuliffe, G.A.; Takahashi, T.; Lee, M.R., (2020). Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int. J. Life Cycle Assess., 25: 208-221 **(14 Pages)**.

Mehmood, Y.; Arshad, M.; Kächele, H., (2022). Effects of wastewater reuse on perceived health risks of farmers in Pakistan: Application of the zero-inflated poisson regression model. J. Cleaner Prod., 133430: 1-11 **(11 Pages)**.

Mio, A.; Fermeglia, M.; Favi, C., (2022). A critical review and normalization of the life cycle assessment outcomes in the naval sector. Articles description. J. Cleaner Prod., 133476: 1-22 **(22 Pages)**.

Mizik, T., (2023). How can precision farming work on a small scale? A systematic literature review. Precis. Agric., 24(1): 384-406 **(23 Pages)**.

Mo, W.; Xiong, Z.; Leong, H.; Gong, X.; Jiang, L.; Xu, J.; Su, S.; Hu, S.; Wang, Y.; Xiang, J., (2022). Processes simulation and environmental evaluation of biofuel production via Co-pyrolysis of tropical agricultural waste. Energy. 123016: 1-13 **(13 Pages)**.

Mohammadi, A.; Cowie, A.; Anh Mai, T.L.; de la Rosa, R.A.; Kristiansen, P.; Brandão, M.; Joseph, S., (2016). Biochar use for climate-change mitigation in rice cropping systems. J. Cleaner Prod., 116: 61-70 **(10 Pages)**.

Mohammadi, A.; Cowie, A.L.; Anh Mai, T.L.; Brandão, M.; Anaya de la Rosa, R.; Kristiansen, P.; Joseph, S., (2017). Climate-change and health effects of using rice husk for biochar-compost: Comparing three pyrolysis systems J. Cleaner Prod., 162: 260-272 **(13 Pages)**.

Mondal, S.; Palit, D. (2022). Challenges in natural resource management for ecological sustainability. in: Natural resources conservation and advances for sustainability, Elsevier. 29-59 **(31 Pages)**.

Mufti, M.; Fathurahman, M.R., (2022). Penyuluhan pemanfaatan limbah pertanian untuk pakan ternak alternatif menggunakan mesin pencacah rumput multifungsi dengan proses amoniase pada kelompok ternak makmur Desa Kebondalem, Jombang. Sarwahita. 19: 583-594 **(12 Pages)**.

Muhie, S.H., (2022). Novel approaches and practices to sustainable agriculture. J. Agric. Food Res., 100446: 1-11 **(11 Pages)**.

Mujtaba, M.; Fraceto, L.; Fazeli, M.; Mukherjee, S.; Savassa, S.M.; de Medeiros, G.A.; Santo Pereira, A.d.E.; Mancini, S.D.; Lipponen, J.; Vilaplana, F., (2023). Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics. J. Cleaner Prod., 136815: 1-23 **(23 Pages)**.

Nasution, M.A.; Wibawa, D.S.; Ahamed, T.; Noguchi, R., (2018). Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia. J. Cleaner Prod., 184: 1028-1040 **(13 Pages)**.

Nayal, F.S.; Mammadov, A.; Ciliz, N., (2016). Environmental assessment of energy generation from agricultural and farm waste through anaerobic digestion. J. Environ. Manage., 184: 389-399 **(11 Pages)**.

Nguyen, T.D.P.; Le, T.V.A.; Show, P.L.; Nguyen, T.T.; Tran, M.H.; Tran, T.N.T.; Lee, S.Y., (2019). Bioflocculation formation of microalgae-bacteria in enhancing microalgae harvesting and nutrient removal from wastewater effluent. Bioresour. Technol., 272: 34-39 **(6 Pages)**.

Nigussie, Z.; Tsunekawa, A.; Haregeweyn, N.; Tsubo, M.; Adgo, E.; Ayalew, Z.; Abele, S., (2021). The impacts of Acacia decurrens plantations on livelihoods in rural Ethiopia. Land Use Policy., 104928: 1-12 **(12 Pages)**.

Onat, N.C.; Kucukvar, M., (2022). A systematic review on sustainability assessment of electric vehicles: Knowledge gaps and future perspectives. Environ. Impact Assess. Rev., 106867: 1-13 **(13 Pages)**.

Onyeaka, H.; Tamasiga, P.; Nwauzoma, U.M.; Miri, T.; Juliet, U.C.; Nwaiwu, O.; Akinsemolu, A.A., (2023). Using artificial intelligence to tackle food waste and enhance the circular economy: maximising resource efficiency and minimising environmental impact: A Review. Sustainability. 15(13): 1-20 **(20 Pages)**.

Pantusa, D.; Saponieri, A.; Tomasicchio, G.R., (2023). Assessment of coastal vulnerability to land-based sources of pollution and its application in Apulia, Italy. Sci. Total Environ. , 163754: 1-12 **(12 Pages)**.

Petrillo, A.; Colangelo, F.; Farina, I.; Travaglioni, M.; Salzano, C.; Cioffi, R., (2022). Multi-criteria analysis for Life Cycle Assessment and Life Cycle Costing of lightweight artificial aggregates from industrial waste by double-step cold bonding palletization. J. Cleaner Prod.,131395: 1-14 **(14 Pages)**.

Phuang, Z.X.; Lin, Z.; Liew, P.Y.; Hanafiah, M.M.; Woon, K.S., (2022). The dilemma in energy transition in Malaysia: A comparative life cycle assessment of large scale solar and biodiesel production from palm oil. J. Cleaner Prod., 131475: 1-13 **(13 Pages)**.

Pratibha, G.; Srinivas, I.; V. Rao, K.; M.K. Raju, B.; Shanker, A.K.; Jha, A.; Uday Kumar, M.; Srinivasa Rao, K.; Sammi Reddy, K., (2019). Identification of environment friendly tillage implement as a strategy for energy efficiency and mitigation of climate change in semiarid rainfed agro ecosystems. J. Cleaner Prod., 214: 524-535 **(12 Pages)**.

Priyambada, I.; Budihardjo, M.; Al Qadar, S.; Puspita, A., (2023). Bibliometric analysis for sustainable food waste using multicriteria decision. Global J. Environ. Sci. Manage., 9(SI): 271-300 **(30 Pages)**.

Puspita, A.S.; Budihardjo, M.A.; Samadikun, B.P., (2023). Evaluating coconut fiber and fly ash composites for use in landfill retention layers. Global Nest J., 25(4): 1-7 **(7 Pages)**.

Qin, T.; She, L.; Wang, Z.; Chen, L.; Xu, W.; Jiang, G.; Zhang, Z., (2022). The Practical Experience of “Zero Waste City” Construction in Foshan City Condenses the Chinese Solution to the Sustainable Development Goals. Sustainability. 14(19): 1-16 **(16 Pages)**.

Rahimi, Z.; Anand, A.; Gautam, S., (2022). An overview on thermochemical conversion and potential evaluation of biofuels derived from agricultural wastes. Energy Nexus, 100125: 1-30 **(30 Pages)**.

Rani, G.M.; Pathania, D.; Umapathi, R.; Rustagi, S.; Huh, Y.S.; Gupta, V.K.; Kaushik, A.; Chaudhary, V., (2023). Agro-waste to sustainable energy: A green strategy of converting agricultural waste to nano-enabled energy applications. Sci. Total Environ., 162667: 1-28 **(28 Pages)**.

Rashedi, A.; Gul, N.; Hussain, M.; Hadi, R.; Khan, N.; Nadeem, S.G.; Khanam, T.; Asyraf, M.; Kumar, V., (2022). Life cycle environmental sustainability and cumulative energy assessment of biomass pellets biofuel derived from agroforest residues. PLoS One, 17(10): 1-18 **(18 Pages)**.

Read, Q.D.; Muth, M.K., (2021). Cost-effectiveness of four food waste interventions: Is food waste reduction a “win–win?”. Resour. Conserv. Recycl., 105448: 1-10 **(10 Pages)**.

Robb, S.; Dargusch, P., (2018). A financial analysis and life-cycle carbon emissions assessment of oil palm waste biochar exports from Indonesia for use in Australian broad-acre agriculture. Carbon Manage., 9(2): 105-114 **(10 Pages)**.

Sabet, H.; Moghaddam, S.S.; Ehteshami, M., (2023). A comparative life cycle assessment (LCA) analysis of innovative methods employing cutting-edge technology to improve sludge reduction directly in wastewater handling units. J. Water Process Eng., 103354: 1-13 **(13 Pages)**.

Samela, C.; Imbrenda, V.; Coluzzi, R.; Pace, L.; Simoniello, T.; Lanfredi, M., (2022). Multi-decadal assessment of soil loss in a Mediterranean region characterized by contrasting local climates. Land. 11(7): 1-25 **(25 Pages)**.

Saravanan, A.; Kumar, P.S.; Jeevanantham, S.; Karishma, S.; Tajsabreen, B.; Yaashikaa, P.; Reshma, B., (2021). Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. Chemosphere. 130595: 1-15 **(15 Pages)**.

Shaheen, J.; Fseha, Y.H.; Sizirici, B., (2022). Performance, life cycle assessment, and economic comparison between date palm waste biochar and activated carbon derived from woody biomass. Heliyon. 8(12): 1-13 **(13 Pages)**.

Shaikh, T.A.; Rasool, T.; Lone, F.R., (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. Comput. Electron. Agric., 107119: 1-29 **(29 Pages)**.

Sharma, H.; Kumar, H.; Mangla, S.K., (2023a). Enablers to computer vision technology for sustainable E-waste management. J. Cleaner Prod., 137396: 1-16 **(16 Pages)**.

Sharma, P.; Bano, A.; Verma, K.; Yadav, M.; Varjani, S.; Singh, S.P.; Tong, Y.W., (2023b). Food waste digestate as biofertilizer and their direct applications in agriculture. Bioresour. Technol. Rep., 101515: 1-12 **(12 Pages)**.

Shokri, A.; Fard, M.S., (2023). Water-energy nexus: Cutting edge water desalination technologies and hybridized renewable-assisted systems; challenges and future roadmaps. Sustainable Energy Technol. Assess., 103173: 1-18 **(18 Pages)**.

Smith, J.; Yeluripati, J.; Smith, P.; Nayak, D.R., (2020). Potential yield challenges to scale-up of zero budget natural farming. Nat. Sustainability. 3(3): 247-252 **(6 Pages)**.

Sparrevik, M.; Lindhjem, H.; Andria, V.; Fet, A.M.; Cornelissen, G., (2014). Environmental and socioeconomic impacts of utilizing waste for biochar in rural areas in Indonesia–a systems perspective. Environ. Sci. Technol., 48(9): 4664-4671 **(5 Pages)**.

Starek-Wójcicka, A.; Stoma, M.; Osmólska, E.; Rydzak, L.; Sobczak, P. 2022. Economic effects of food industry waste management in the context of sustainable development. In: Pascuzzi, S., Santoro, F. (eds) Farm Machinery and Processes Management in Sustainable Agriculture. FMPMSA 2022. Lecture Notes Civil Eng., 289: 97-106 **(10 Pages)**.

Tedesco, D.; de Almeida Moreira, B.R.; Júnior, M.R.B.; Maeda, M.; da Silva, R.P., (2023). Sustainable management of sweet potatoes: A review on practices, strategies, and opportunities in nutrition-sensitive agriculture, energy security, and quality of life. Agric. Syst., 103693: 1-11 **(11 Pages)**.

Tong, H.; Shen, Y.; Zhang, J.; Wang, C.-H.; Ge, T.S.; Tong, Y.W., (2018). A comparative life cycle assessment on four waste-to-energy scenarios for food waste generated in eateries. Appl. Energy., 225: 1143-1157 **(15 Pages)**.

Torkayesh, A.E.; Rajaeifar, M.A.; Rostom, M.; Malmir, B.; Yazdani, M.; Suh, S.; Heidrich, O., (2022). Integrating life cycle assessment and multi criteria decision making for sustainable waste management: key issues and recommendations for future studies. Renewable Sustainable Energy Rev., 112819: 1-24 **(24 Pages)**.

Trummer, P.; Ammerer, G.; Scherz, M., (2022). Sustainable consumption and production in the extraction and processing of raw materials—measures sets for achieving SDG target 12.2. Sustainability. 14(17): 1-18 **(18 Pages)**.

Tseng, M.L.; Ha, H.M.; Tran, T.P.T.; Bui, T.D.; Chen, C.C.; Lin, C.W., (2022). Building a data-driven circular supply chain hierarchical structure: Resource recovery implementation drives circular business strategy. Bus Strategy Environ., 31(5): 2082-2106 **(25 Pages)**.

Vasseghian, Y.; Arunkumar, P.; Joo, S.-W.; Gnanasekaran, L.; Kamyab, H.; Rajendran, S.; Balakrishnan, D.; Chelliapan, S.; Klemeš, J.J., (2022). Metal-organic framework-enabled pesticides are an emerging tool for sustainable cleaner production and environmental hazard reduction. J. Cleaner Prod., 133966: 1-13 **(13 Pages)**.

Vu, T.; Vu, D.; Jensen, L.; Sommer, S.; Bruun, S., (2015). Life cycle assessment of biogas production in small-scale household digesters in Vietnam. Asian-Australas. J. Anim. Sci., 28(5): 716-729 **(14 Pages)**.

Wahyono, Y.; Hadiyanto, H.; Gheewala, S.H.; Budihardjo, M.A.; Adiansyah, J.; Widayat, W.; Christwardana, M., (2023). Life cycle assessment for evaluating the energy balance of the multi-feedstock biodiesel production process in Indonesia. Int. J. Ambient Energy. 44(1): 1255-1270 **(15 Pages)**.

Wang, Q.-L.; Li, W.; Gao, X.; Li, S.-J., (2016). Life cycle assessment on biogas production from straw and its sensitivity analysis. Bioresour. Technol., 201: 208-214 **(15 Pages**).

Wang, Y.; Wu, X.; Tong, X.; Li, T.; Wu, F., (2018). Life cycle assessment of large-scale and household biogas plants in northwest China. J. Cleaner Prod., 192: 221-235 **(15 Pages)**.

Wu, L.; Elshorbagy, A.; Pande, S.; Zhuo, L., (2021). Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. Resour. Conserv. Recycl., 105192: 1-14 **(14 Pages)**.

Yadav, P.; Samadder, S.R., (2018). A critical review of the life cycle assessment studies on solid waste management in Asian countries. J. Cleaner Prod., 185: 492-515 **(24 Pages)**.

Yang, X.; Han, D.; Zhao, Y.; Li, R.; Wu, Y., (2020). Environmental evaluation of a distributed-centralized biomass pyrolysis system: A case study in Shandong, China. Sci. Total Environ., 136915: 1-11 **(11 Pages)**.

Zeug, W.; Bezama, A.; Thrän, D., (2023). Life cycle sustainability assessment for sustainable bioeconomy, societal-ecological transformation and beyond. in: Progress in Life cycle assessment 2021, Springer. 131-159 **(29 Pages)**.

Zhu, X.; Labianca, C.; He, M.; Luo, Z.; Wu, C.; You, S.; Tsang, D.C., (2022). Life-cycle assessment of pyrolysis processes for sustainable production of biochar from agro-residues. Bioresour. Technol., 127601: 1-13 **(13 Pages)**.

Zoppi, G.; Tito, E.; Bianco, I.; Pipitone, G.; Pirone, R.; Bensaid, S., (2023). Life cycle assessment of the biofuel production from lignocellulosic biomass in a hydrothermal liquefaction–aqueous phase reforming integrated biorefinery. Renewable Energy. 206: 375-385 **(11 Pages)**.

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