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CONTENTS

Volume 9, Number 3, Summer 2023

1.	Land surface temperature changes caused by land cover/ land use properties and their impact on rainfall characteristics **A. Suharyanto; A. Maulana; D. Suprayogo; Y.P. Devia; S. Kurniawan (INDONESIA)**	353
2.	Response surface methodology and adaptive neuro-fuzzy inference system for adsorption of reactive orange 16 by hydrochar **J. Oliver Paul Nayagam; K. Prasanna (INDIA)**	373
3.	Relationship between chlorophyll-a, sea surface temperature, and sea surface salinity **M.N. Hidayat; R. Wafdan; M. Ramli; Z.A. Muchlisin; S. Rizal (INDONESIA)**	389
4.	Social learning activities to improve community engagement in waste management program **S. Sunarti; R.S.Y. Zebua; J.H. Tjakraatmadja; A. Ghazali; B. Rahardyan; K. Koeswinarno; S. Suradi; N. Nurhayu; R.H.A. Ansyah (INDONESIA)**	403
5.	Toxicity of nickel oxide nanoparticle in Capoeta fusca, using bioaccumulation, depuration, and histopathological changes **J. Kharkan; M.H. Sayadi; M. Hajiani; M.R. Rezaei; M. Savabieasfahani (IRAN)**	427
6.	Land use variation impacts on trace elements in the tissues and health risks of a commercial fish **N.D. Takarina; O.M. Chuan; T.G. Pin; I. Femnisya; A. Fathinah; A.N.B. Ramadhan; R. Hermawan; A. Adiwibowo (INDONESIA)**	445
7.	Spatial delineation on marine environmental characteristics using fuzzy c-means clustering method **E.D. Lusiana, S. Astutik, N. Nurjannah, A.B. Sambah (INDONESIA)**	463
8.	Performance of sewage sludge reuse in the manufacturing of fired bricks **K. Moulato; M. Ammari; L. Ben Allal (MOROCCO)**	477
9.	Cadmium and lead uptake by wild swamp eel in the populous river **N. Nurhasanah; L. Sulistyowati; E. Riani; M.R. Cordova (INDONESIA)**	497
10.	Modeling the tropical fish community related to land uses and environmental determinants **N.D. Takarina; O.M. Chuan; M.I. Afifudin; L. Tristan; I. Arif; A. Adiwibowo (INDONESIA)**	515
11.	Proximate values a Proximate values and elemental analysis in wheat and soybean using inductively coupled plasma mass spectrometry **G. Kowmudi; V. Rashmi; K. Anoop; N. Krishnaveni; S. Naveen (INDONESIA)**	531

12.	Sub-surface flow constructed wetland for the treatment of sewage generated in a municipal parks **A.M. Vazquez; A. Samudio-Oggero; H.D. Nakayama; I. Cantero-García (PARAGUAY)**	545
13.	Sustainability index analysis of microalgae cultivated in biorefinery palm oil mill effluent **A.D. Santoso; T. Handayani; D. Pinardi; K. Kusrestuwardani; N. Widyastuti; I.N. Djarot; J. Haryanti; A.I. Sitomurni; H. Apriyanto (INDONESIA)**	559
14.	Green transformational and transactional leadership in fostering green creativity among university students **N. Saif; G.G.G. GOH; J.W. Ong; I.U. Khan (PAKISTAN/ MALAYSIA)**	577
15.	Urban green space during the Coronavirus disease pandemic with regard to the socioeconomic characteristics **R. Setiowati; R.H. Koestoer; K. Mizuno; H.S. Hasibuan (INDONESIA/ JAPAN)**	589
16.	Developing a composite-based constitutive model for municipal solid waste **M.R. Yousefi; A. Noorzad; M.J. Mahmoodi (IRAN)**	607
17.	Water security assessment framework for deltas of the transboundary river basins **T.H. Truong, L.T.T. Nguyen, D.D. Nguyen, T. Pham, T.M. Vu, P.H. Nguyen, Q.T. Nguyen (VIETNAM)**	619
18.	Relationship between landscape and river ecosystem services **M. Dede; S. Sunardi; K.C. Lam; S. Withaningsih (INDONESIA)**	637

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CASE STUDY

Land surface temperature changes caused by land cover/ land use properties and their impact on rainfall characteristics

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aims to determine the relationships between land cover presented by vegetation index and land surface temperature, between vegetation index and the built-up index, between built-up index and land surface temperature, and between land surface temperature and rainfall characteristics in East Java Province, Indonesia.

METHODS: Three cities and four regencies were used as examples. Landsat imagery scanned in 1995, 2001, 2015, and 2020 were used. Daily rainfall data recorded in the same years with Landsat data are used. The pixel values along the urban heat island line were used to analyze the interrelationships between vegetation index, built-up index, and land surface temperature. The land surface temperature and daily rainfall data from each Thiessen polygon were used to analyze the relationship between land surface temperature and rainfall characteristics. Image processing analysis was used to analyze the vegetation index, built-up index, and land surface temperature. The mathematical interrelationship between vegetation index, built-up index, land surface temperature, and rainfall intensity was analyzed using linear regression.

FINDINGS: The results of the analysis show that the relationship between vegetation index and built-up index is inversely proportional and with land surface temperature is nearly inversely proportional to a coefficient of determination greater than 0.5. For the relationship between the built-up index and land surface temperature, the results of the analysis show that both have a directly proportional relationship, with a significant coefficient of determination (R2>0.5). For the relationship between land surface temperature and rainfall characteristics, the results of the analysis show that land surface temperature has a directly proportional but weak relationship with rainfall intensity and an inversely proportional but weak relationship with the number of rainfall days. Decreasing environmental conditions indicated by decreasing vegetation index will influence increasing land surface temperature and its effect on increasing rainfall intensity and decreasing rainfall days.

CONCLUSION: Changes in land use/land cover are characterized by a change in vegetation cover to built-up land. These changes affect the land surface temperature. Changes in land surface temperature affect the occurrences of rainfall intensity. When the vegetation index decreases, the built-up index increases, and the land surface temperature increases as well. The increase in land surface temperature will increase the rainfall intensity. Satellite remote sensing imagery is effective and efficient for analyzing vegetation index, built-up index, and land surface temperature.

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INTRODUCTION

Population growth in Indonesia, particularly in East Java Province, follows the exponential function (BPS-SJTP, 2021; Nicolau *et al.,* 2018). Food, clothing, and household consumption increase rapidly to fulfill the basic needs of human life. To increase food production, agricultural land needs to be expanded. Agricultural land is located in flat areas but is currently being expanded to hilly areas. To meet the housing needs, the city grows from suburban areas, such as agricultural or forest areas, to urban areas. This activity are converted pervious areas into impervious areas. This phenomenon will rapidly change land use/land cover (LULC) from vegetation areas to non-vegetation areas (Moslenko *et al.,* 2020; Stehfest *et al.,* 2019), which will affect the increase of the land surface temperature (LST) (Guha *et al.,* 2018; Hua and Ping, 2018). Garouani *et al*. (2021) concluded that LULC change has an important consequence in hydrology. Predicting precipitation until the 21century is affected by LST (Himayoun *et al*, 2020). Hu *et al*. (2020) mentioned that trend surface runoff has consistent with the trend of impervious area, and Shiraki and Shigeta (2013) was concluded there is a relation between LST and convective precipitation frequency. From those studied, no discussion of the relationship between LST and rainfall intensity and the number of rainfall days (NRD). The rainfall characteristics are important as input data to peak discharge analysis. The peak discharge data are most important in flood analysis, water structure design, and soil erosion analysis (Anache *et al.,* 2017; Kovář *et al.,* 2012; Jiang *et al.,* 2019; Mapiam *et al.,* 2014). In this study, the effect of LST on the rainfall characteristics especially in rainfall intensity and NRD needs to be evaluated. Satellite remote sensing data are one of the powerful data used to analyze the LULC change from vegetation areas to non-vegetation areas and LST change (Derdouri *et al.,* 2021; Ferrelli *et al.,* 2018). One of them is Landsat imagery data. LULC change can be analyzed using multi-spatial and multi-temporal satellite remote sensing data. The normalized difference vegetation index (NDVI) is one of the vegetation indices commonly used to analyze plant greenness (Mondino *et al.,* 2016; Turvey and McLaurin, 2012). The value of NDVI ranges from −1 to + 1. Values between 0 and −1 indicate that the land is covered by non-vegetation objects, such as dead plants, stones, roads, houses, and barren land. The degree or level of land covered by green foliage or plants is indicated by the NDVI with values from 0 to +1 (Chang *et al.,* 2021; Reid *et al.,* 2018). Zero indicates the lowest area covered by green foliage or plants, and +1 indicates the highest area covered by green foliage or plants. In previous studies, many researchers concluded that LST is related to the pattern of LULC change, such as urbanized, vegetation, and water areas (Almouctar, 2021; Maselli, 2012; Samal and Gedam, 2017). Here the LULC change can be represented by the change of NDVI. The plant greenness will determine the level of solar radiation absorbed by the leaves. The area with a high level of plant greenness, which is indicated by the NDVI value of +1, will have an LST lower than that of the area with a low level of plant greenness. The relationship between NDVI and LST will be discussed as the first objective of this study. The LULC change can also be indicated by the change of the normalized difference built-up index (NDBI). This index indicates the level of the built-up area, particularly in the urbanized area (Badlani *et al.,* 2017; Ibrahim, 2017). NDBI is the opposite of NDVI. NDBI indicates the built-up area (impervious area), including barren land, whereas NDVI indicates land covered by green foliage or plants, including vegetation, agricultural land, parks, and gardens, as well as open space. The relationship between NDVI and NDBI can be predicted to have a negative correlation. This phenomenon will also be discussed as the second objective of this study. Climate change is one of the phenomena that should be considered in the civil work plan. One of the climate change indicators is the increase of LST. Devi *et al*. (2020) concluded that deforestation has an effect on LST, and Liu *et al*. (2021) mentioned that LST change varied over different regions. A high LST and a low NDVI will affect the decrease of rainfall and soil moisture (Shiraki and Shigeta, 2013). Compared with LST, land elevation has a more significant effect on increasing the frequency of convective rainfall than surface temperature (Peng *et al.,* 2020; Shiraki and Shigeta, 2013). The relationship between LST and rainfall characteristics needs to be analyzed, and it is the third objective of this work. East Java Province, Indonesia is one of the provinces in Indonesia with rapid LULC change (BPS-SJTP, 2021; Indarto and Hakim, 2021). The second largest city in Indonesia, i.e., Surabaya City, is located in East Java Province. As the second largest city, the development of Surabaya

City is fast, and LULC change is occurring rapidly (BPS-SSM, 2021). A well-known resort area, i.e., Batu City, is located in East Java Province. This city was established in 2004, and LULC change is occurring rapidly. Under these conditions, the LULC change represented by NDVI and its effect on the LST and rainfall characteristics in the aforementioned areas need to be analyzed. The study will be conducted in three cities and four regencies in East Java Province. The Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and Operational Land Imager (OLI) imageries recorded in 1995, 2000, 2015, and 2020 are used in this study. Daily rainfall in the same years recorded at the rainfall stations located surrounding each study area is used as input data in the analysis of the relationship between LST and rainfall characteristics. Three analyses i.e., relationship between NDVI and LST, between NDVI and NDBI, and between LST and rainfall characteristics will be analyzed in this study. Given that climate change is occurring rapidly, research on the effects of LULC change represented by NDVI on the LST, NDBI, and rainfall characteristics in East Java Province needs to be conducted. The main contribution of this study is to quantitatively analyze the LULC change in some areas in East Java Province from 1995 to 2020 using multi-temporal Landsat imagery. The main purpose of this study is to determine the relationship between LULC change and rainfall characteristics. It can be expected that the results of this study can be implemented to predict the rainfall characteristics based on LULC change, particularly in East Java Province. This study has been carried out in East Java Province Indonesia with 3 cities and 4 regencies in the years 1995, 2001, 2015, and 2020.

MATERIALS AND METHODS

Study area

The study area is three cities and four regencies in East Java Province, Indonesia. The three cities are Surabaya, Malang, and Batu. Surabaya City is located in a lowland area with a flat topography with an elevation of 3–6 meters (m) above sea level and bounded by sea and land. Malang and Batu cities are located in a hilly area and bounded by land. The elevation of Malang City is 445–526 m above sea level, and the average elevation of Batu City is 897 m above sea level. The four regencies are Malang, Probolinggo, Sampang, and Tuban. Malang Regency is located in the southern part of East Java Province, and its southern area is facing the Indian Ocean. The elevation of Malang Regency is 0–3,600 m above sea level. Probolinggo Regency is located in the middle of East Java Province, and its northern area is facing the Madura Strait. The elevation of Probolinggo Regency is 0–1,500 m above sea level. Across Probolinggo Regency is Sampang Regency. Sampang Regency is located in the middle of Madura Island, and its southern area is facing the Madura Strait and its northern area is facing the Java Sea. The elevation of the Sampang Regency is 0–375 m above sea level. Tuban Regency is located in the western part of East Java Province, and its northern area is facing the Java Sea. The elevation of Tuban Regency is 0–500 m above sea level. A summary of the geographical and demographic conditions of the study area is shown in Table 1. Based on these conditions, Surabaya City represents a high-density population and lowland area, and Malang and Batu cities represent hilly areas and growing cities. Meanwhile, Malang Regency represents areas located in the southern part of East Java Province, Probolinggo Regency represents areas located in the middle part of East Java Province, Sampang Regency represents areas located in the middle of Madura Island, and Tuban Regency represents areas located in the northern part of East Java Province. The location of the study area is shown in Fig. 1. The aims of the current study can be summarized as: 1) To explore the LULC changes represented by NDVI, NDBI, and LST from Landsat imageries data; 2) To understand interrelationships between NDVI, NDBI, and LST; and 3) To find the

Table 1: Geographic and demographic conditions of the study locations

No.	Location	Area (km^2)	Population	Topography
1.	Batu City	199.09	213.046	Hilly
2.	Malang City	110.06	843.810	Hilly
3.	Surabaya City	326.81	2,970,000	Flat
4.	Malang Regency	3,530.65	2,654,448	Flat–mountainous
5,	Probolinggo Regency	1,696.17	1,152,537	Flat–mountainous
6.	Sampang Regency	1,233.30	969,694	Flat–hilly
7.	Tuban Regency	1,839.94	1,198,012	Flat–hilly

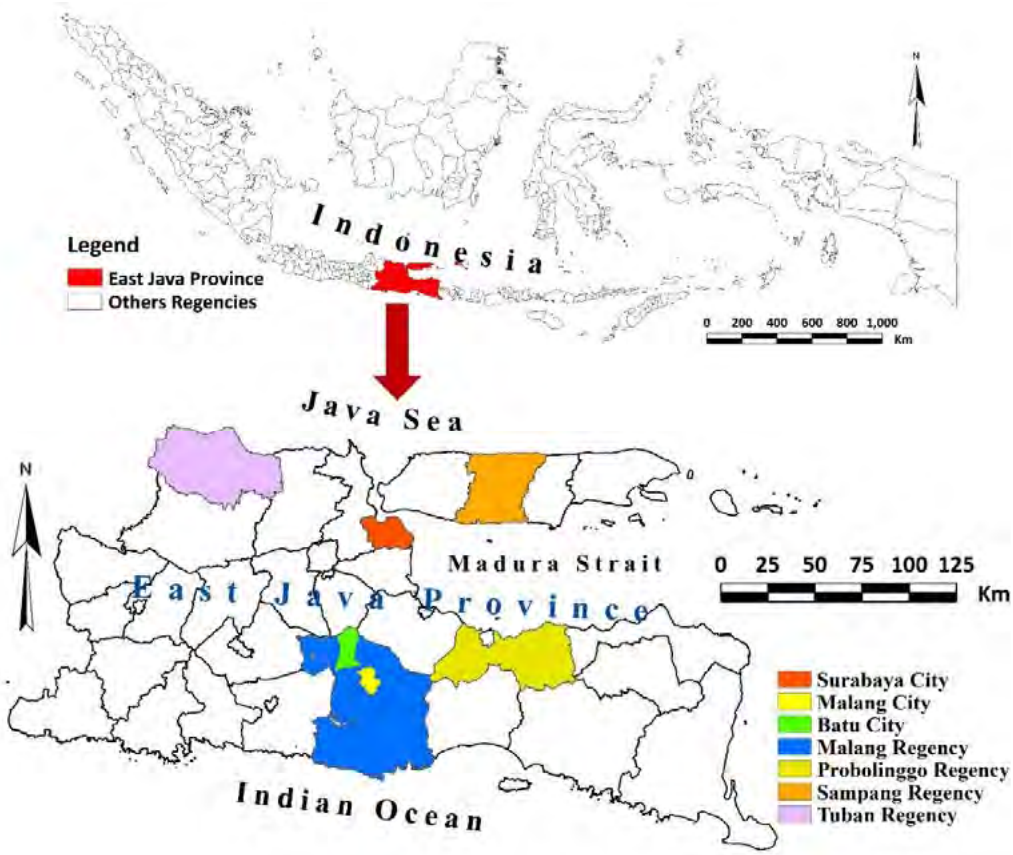

Fig. 1: Geographic location of the study area in East Java Province, Indonesia

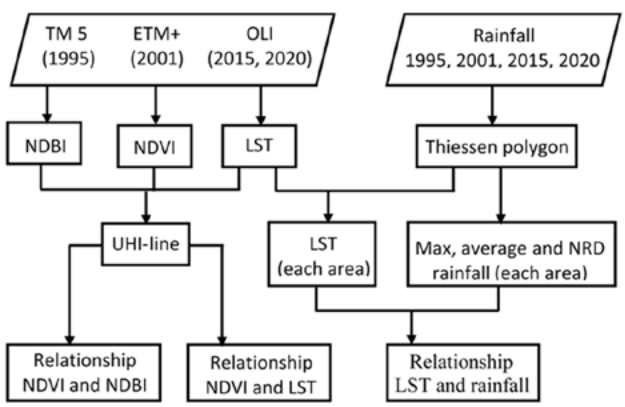

Fig. 2: Flow diagram of the study method

relationship between LST and rainfall characteristics.

In principle, the methodology used in this study includes image processing, rainfall data analysis using the Thiessen polygon method, and regression analysis. The diagram of the overall methodology used in this study is shown in Fig. 2.

Image processing

Many satellites are recording the earth's surface conditions. Among them is Landsat. The Landsat satellite is equipped with the TM, ETM+, and OLI sensors to scan the earth's surface conditions. The imageries scanned by these sensors are used in this

research. Image processing was conducted to achieve the study goals, which include determining the NDVI, LST, urban heat island (UHI), and NDBI. NDVI indicates the LULC change based on the greenness level in the study area. The Geographic Information System (GIS) software was used for image processing.

Extraction of NDVI

NDVI is calculated based on the ratio of visible to near-infrared (NIR) light absorbed and reflected by plants. For Landsat 5 TM and Landsat 7 ETM+, visible and NIR light are recorded at Bands 3 and 4, and for Landsat 8 OLI, visible and NIR light are recorded at Bands 4 and 5. The value of NDVI ranges from −1 to +1. The values from −1 to 0 indicate that the area is covered by dead plants, rock, water, bare land, and built-up areas (Ozyavuz *et al.,* 2015). The NDVI values ranging from 0 to 0.33 indicate unhealthy plants, 0.33 to 0.66 indicate moderately healthy plants, and 0.66 to 1 indicate very healthy plants (Chen *et al.,* 2021). The formula used to calculate the NDVI values for Landsat TM and ETM+ is expressed in Eq. 1 (Osyavus *et al.,* 2015), and the formula used to calculate the NDVI value for Landsat 8 OLI, using Eq. 2 (Chang *et al.,* 2021).

$$\text{NDVI} = (\text{Band 4} - \text{Band 3})/(\text{Band 4} + \text{Band 3}) \quad (1)$$

$$\text{NDVI} = (\text{Band 5} - \text{Band 4})/(\text{Band 5} + \text{Band 4}) \quad (2)$$

Extraction of NDBI

In principle, urbanization is the change of land cover from pervious areas to impervious areas caused by the overlay of the land surface by impervious materials, such as concrete, asphalt, and roof. One indicator that can be used to detect the urbanization rate is NDBI, which is generated from satellite images. The formula used to calculate the NDBI is expressed in Eq. 3 (Badlani *et al.,* 2017; Bonafoni *et al.,* 2016). For Landsat TM and ETM+, short wave infrared (SWIR) and NIR are represented by Bands 5 and 4, respectively. For Landsat 8 OLI, SWIR and NIR are represented by Bands 6 and 5, respectively. The value of NDBI ranges between −1 and +1. A large NDBI value indicates that the area has large proportions of built-up and construction areas (Firozjaei *et al.,* 2019).

$$\text{NDBI} = (\text{SWIR} - \text{NIR})/(\text{SWIR} + \text{NIR}) \quad (3)$$

Extraction of LST from Landsat TM, ETM+, and OLI

LST is a natural phenomenon that can be detected using satellite remote sensing data. For Landsat 5 TM and Landsat 7 ETM+, LST can be generated from Band 6. For Landsat 8 OLI, LST is analyzed using Band 10 or 11. The formula used to calculate LST from Landsat TM and ETM is expressed using Eq. 4 (Grover and Singh, 2015; Mustafa *et al.,* 2020; Ranagalage *et al.,* 2017).

$$L_\lambda = ((L_{max\lambda} - L_{min\lambda})/(QCAL_{max} - QCAL_{min}))*((QCAL - QCAL_{min}) + L_{min\lambda}), \quad (4)$$

Where, L_λ is the temperature of the satellite sensor (brightness radiance), $L_{max\lambda}$ is the maximum radiance, $L_{min\lambda}$ is the minimum radiance, $QCAL_{max}$ is the quantized calibrated maximum, $QCAL_{min}$ is the quantized calibrated minimum, and *QCAL* is the digital number (DN) of Band 6. Based on the brightness radiance, LST can be calculated using Eq. 5 (Almeida *et al.,* 2021).

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_{\ddot{e}}} + 1\right)} \quad (5)$$

Where, *T* is the LST (Kelvin), K_1 is Constant 1, and K_2 is Constant 2. The values of K_1 and K_2 can be found in the Landsat 7 (L7) Data Users Handbook (USGS, 2019). To convert the LST from degrees Kelvin to degrees Celsius, 273.15 should be subtracted from *T,* using Eq. 6 (Grover and Singh, 2015).

$$TC = T - 273.15 \quad (6)$$

Where, *TC* is the LST in degrees Celsius.

For Landsat 8 OLI, the calculation to determine the LST can be done as follows. The first step is to calculate the top of atmospheric (TOA) spectral radiance, using Eq. 7 (Hua and Ping, 2018).

$$TOA = M_L * C_{cal} + A_L, \quad (7)$$

Where, M_L is the radiance multiplicative scaling factor (Radiance_Mult_Band_10) obtained from the MTL file on the Landsat data, A_L is the radiance

additive scaling factor (Radiance_Add_Band_10) obtained from the MTL file on the Landsat data, and C_{cal} is the digital value of Band 10. *TOA* can also be calculated using the same equation expressed in Eq. 6.

The second step is to calculate the brightness temperature in degrees Celsius, using Eq. 8 (Garouani *et al.,* 2021).

$$\mathrm{TC} = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda}+1\right)} - 273.15. \tag{8}$$

For Landsat 8 OLI, K_1 and K_2 are the band-specific thermal conversion constants taken from the metadata of the imagery file.

The third step is to calculate the proportional vegetation (PV) using the NDVI, as expressed as Eq. 9 (Alexander, 2020).

$$\mathrm{PV} = \left(\frac{\mathrm{NDVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}}\right)^2 \tag{9}$$

The fourth step is to calculate the error correction (*E*), using Eq. 10 (Guha *et al.,* 2018).

$$E = 0.004 * PV + 0.986. \tag{10}$$

The fifth step is to calculate the LST in degrees Celsius, using Eq. 11 (Ranagalage *et al.,* 2017).

$$\mathrm{LST} = \frac{\mathrm{TC}}{\left\{1+\left[\left(\lambda \mathrm{TC}/\rho\right)\mathrm{Ln}E\right]\right\}}, \tag{11}$$

Where, λ is the DN of Band 10 (λ is the wavelength of emitted radiance (λ = 11.5 µm for Landsat TM Band 6, λ = 10.8 µm for Landsat TIRS Band 10) [Senanayake *et al.,* 2013], ρ = 14,380 ($\rho = h \times c/\sigma$ (1.438×10^{-2} mK)), *TC* is the brightness temperature, σ is the Boltzmann constant (1.38×10^{-23} J/K), *h* is the Planck constant (6.626×10^{-34} Js), *c* is the velocity of light (2.998×10^{8} m/s), and *E* is the land surface emissivity or error correction.

Analyses of UHI

The analysis of the LST is associated with the UHI phenomenon. The UHI is part of the LST located at the center of an urbanized area and depends on where the line of the UHI will be drawn in the study area (Almeida *et al.,* 2021). Normally, the line of the UHI is initially drawn from a suburban area to an urban area and finally reaches another suburban area or crosses another urban area. In this study, this line is called the UHI line. The UHI phenomenon represents the higher atmospheric temperature and LST in the urban area than in the suburban area, which can be used to detect the urbanization rate (Grover and Singh, 2015; Yuan and Bauer, 2007). The increase of UHI is affected by anthropogenic heat generated from traffic, LULC change, and increase of impervious area, and it affects the urban climate because of the exchange of energy and level of conductivity (Alexander, 2020; Neinavaz *et al.,* 2020; Sekertekin and Bonafoni, 2020). The change of LST is closely related to the change of UHI because UHI is part of the LST located at the center of an urbanized area. The values of NDVI, NDBI, and LST along the UHI line will be used as data to analyze their relationship with each other. LST and NDVI have a reverse relationship, i.e., the decrease of NDVI will affect the increase of LST (Arnon *et al.,* 2010; Guha *et al.,* 2018; Hua and Ping, 2018). The increase of LST will affect the change of the local climate, including the change in the rainfall characteristics.

Rainfall characteristics

The rainfall characteristics can be indicated by the maximum, minimum, and average values of rainfall intensity and the NRD in a certain period. The rainfall data are recorded by rainfall stations that are located around an area. Each rainfall station has an influence area. Several methods are employed to analyze the influence area of the rainfall station. One method that is commonly used in hydrologic analysis is the Thiessen polygon method (Brassel and Reif, 2010; Fiedler, 2003). The influence area of the rainfall station is obtained by drawing perpendicular bisectors on lines intersecting near the stations to form a series of polygons, each containing one and only one rainfall station, and leaving the other stations at the center of the polygons, which will vary in size according to the spacing of the stations. Based on the Thiessen polygon of each research area, the LST image of each research area is cropped. The relationship between

the changes of LST in the influence area of each rainfall station and the changes of the maximum, minimum, and average values of rainfall intensity and NRD of each research area will be investigated.

RESULTS AND DISCUSSION

The imagery data used in this study are Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI scanned in 1995, 2001, 2015, and 2020. All of the imagery data were downloaded from the USGS through the USGS Earth Explorer. In the study area, no cloud cover percentage <10% was observed. As a result, 5-year interval imagery data starting in 1995 cannot be obtained. The imageries scanned in 2000 were significantly different from the imageries scanned in 2001. Due to the percentage of cloud cover, the best imageries of ETM+ covering the Probolinggo Regency, Sampang Regency, and Surabaya City was obtained in 2002. The overall imageries used in this study are shown in Table 2. The ArcGIS software was used to analyze the Landsat imagery data.

From Table 2 it can be seen that the satellite images used were scanned between May to August or during dry season in Indonesia. In this season, there are relatively low cloud cover so that a relatively clean images can be obtained. In the result, all images with cloud cover less than 10% can be obtained for this study. The rainfall data were obtained from the East Java Province Water Resources Agency (Dinas Pengairan Provinsi Jawa Timur). The number of rainfall stations used in this study depends on the availability of stations for each research area. Based on the availability of data, the daily rainfall data are used in this study. The maximum, minimum, and average values of rainfall intensity and the NRD data in the same year as the satellite imagery data are used in this study.

Relationship between NDVI and LST

The NDVI of all research areas was calculated using Eqs. 1 or 2. By using these Eqs., the minimum and maximum values of the NDVI of all research areas was analyzed. The result is shown that the negative NDVI decreases year by year, whereas the positive NDVI remains the same year by year. This finding indicates that some areas covered by vegetation were converted into areas covered by manmade materials, built-up areas, or bare land. For example, the 1995 and 2020 NDVI of Malang and Surabaya cities is shown in Fig. 3. This figure shows that the greenness displayed in green colour decreased from 1995 to 2020 to the non-greenness area displayed in brown colour.

If the NDVI in the study area decreases, then solar energy will be reflected and emitted by manmade materials. The manmade materials strongly reflected the solar energy, then the LST will increase. To determine the relationship between NDVI and LST, the LST of the research area needs to be analyzed using Eqs. 4 to 11. For the Landsat 5 TM and Landsat 7 ETM+ imageries, $QCAL_{max}$ is equal to 255 and $QCAL_{min}$ is equal to 1. For Band 6, $L_{max\lambda}$ is equal to 15.303 and

Table 2: Landsat imagery data.

No.	Path/row	Sensor	Acquisition date	Location
1.	118/066	L5-TM	May 24, 1995	Malang Regency Malang City Batu City
2.	118/065	L5-TM	June 25, 1995	Probolinggo Regency Surabaya City
3.	118/065	L5-TM	July 27, 1995	Sampang Regency
4.	119/065	L5-TM	August 03, 1995	Tuban Regency
5.	118/066	L7-ETM	August 04, 2001	Malang Regency Malang City Batu City
6	118/065	L7-ETM	August 23, 2002	Probolinggo Regency Sampang Regency
7	118/065	L7-ETM	May 19, 2002	Surabaya City
8	119/065	L7-ETM	August 27, 2001	Tuban Regency
9	118/066	L8-OLI	June 16, 2015	Malang Regency Malang City Batu City
10	118/065	L8-OLI	June 16, 2015	Probolinggo Regency Surabaya City Sampang Regency
11	119/065	L8-OLI	June 23, 2015	Tuban Regency
12	118/066	L8-OLI	June 13, 2020	Malang Regency Malang City Batu City Probolinggo Regency
13	118/065	L8-OLI	July 31, 2020	Sampang Regency
14	118/065	L8-OLI	June 13, 2020	Surabaya City
15	119/065	L8-OLI	August 23, 2020	Tuban Regency

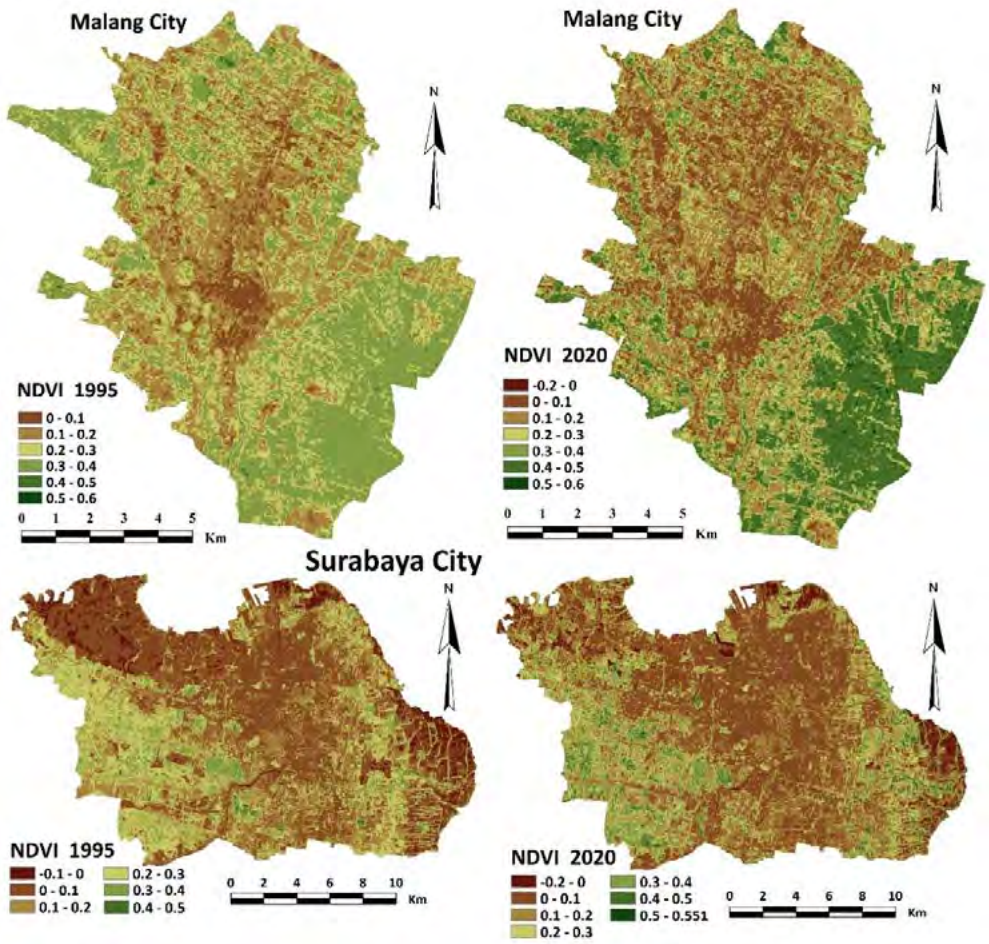

Fig. 3: NDVI of Malang and Surabaya cities in 1995 and 2020

$L_{min\lambda}$ is equal to 1.23. The other parameters used to analyze LST from the Landsat 5 TM and Landsat 7 ETM+ imageries are K_1 and K_2. Here, K_1 is equal to 607.76 and 666.09, and K_2 is equal to 1,260.56 and 1,282.71 for Landsat 5 TM and Landsat 7 ETM+ imageries, respectively. For Landsat 8 OLI, K_1 and K_2 for Band 10 are equal to 774.89 and 1,321.08, respectively. From the MTL file on the Landsat 8 OLI data used in this study, the M_L and A_L values for Band 10 are equal to 0.0003342 and 0.1, respectively. Based on these parameters and the corresponding DN of satellite imagery data, the LST of all research areas was analyzed. The summary of the LST analysis results shows that the maximum and minimum values of LST in all research areas increase year by year from 1995 to 2020. The maximum LST in Surabaya City and Tuban Regency increased. For Surabaya City, the maximum LST increased from 28°C in 1995 to 34°C in 2020, i.e., up to 6°C. This finding indicates that Surabaya City is undergoing rapid urbanization because it is the second largest city in Indonesia. For Tuban Regency, the maximum LST increased from 28°C in 1995 to 37.2°C in 2020, i.e., up to 9.2°C. This finding indicates that Tuban Regency is one of the areas in East Java Province that has many oil mining areas with high demand for oil fuel energy (BPS-STR, 2021). The LST changes from 1995 to 2020 and the LST

imageries of Surabaya City and Tuban Regency are shown in Fig. 4. It is shown that the dark red colour increased from 1995 to 2020, meaning the LST trend increased. The NDVI tends to decrease year by year,

whereas the LST tends to increase year by year. To obtain a clear understanding of these phenomena, the relationship between NDVI and LST needs to be analyzed. To simplify the analysis of this relationship, the picture element (pixel) of the NDVI and LST of each research area generated from the UHI will be compared. The UHI is the occurrence of LST in urbanized areas compared with the LST in suburban areas. In this study, the UHI is represented by a line drawn from a suburban area to a central urban area and another suburban area. In this study, this line is called the UHI line. The pixel values of the NDVI and LST along the UHI line will be compared to determine the relationship between NDVI and LST in all research areas. For example, the UHI line of Probolinggo Regency drawn on the land cover imageries is shown in Fig. 5. The maximum and minimum values of NDVI and LST along the UHI line of all research areas are summarized in Tables 3 and 4. Table 3 shows that the minimum value of NDVI in 2001 is negative, which indicates that some pixels along the UHI line are not covered by vegetation. The minimum values of NDVI in the other years are all positive, which indicates that some pixels along the UHI line are covered by vegetation. This phenomenon indicates that, after the reformation era (i.e., 1998), deforestation in East Java Province occurred poorly. Tabel 4 shows that the LST almost increase year by year. A decrease in NDVI causes the energy of sunlight to be reflected and emitted strongly and causes the LST to rise. The relationship between NDVI and LST was depicted in graphs. The trend line was drawn, and regression analysis was conducted. Each research area has four graphs for 1995,

2001, 2015, and 2020. Therefore, a total of 28 graphs are generated for the relationship between NDVI and LST in the entire research area. Six of the 28 graphs are shown in Fig. 6 as examples. The summary of 24 regression analyses, which consist of regression equations and coefficients of determination, is shown

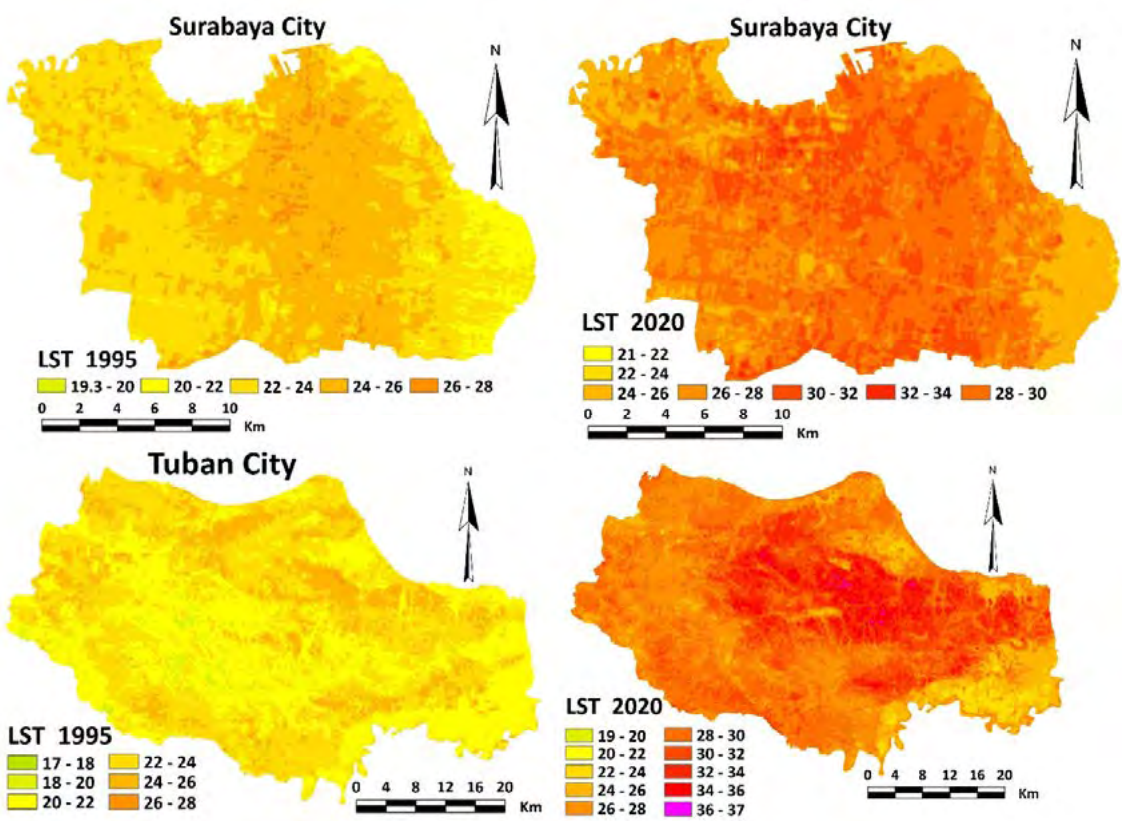

Fig. 4: LST of Surabaya City and Tuban Regency in 1995 and 2020

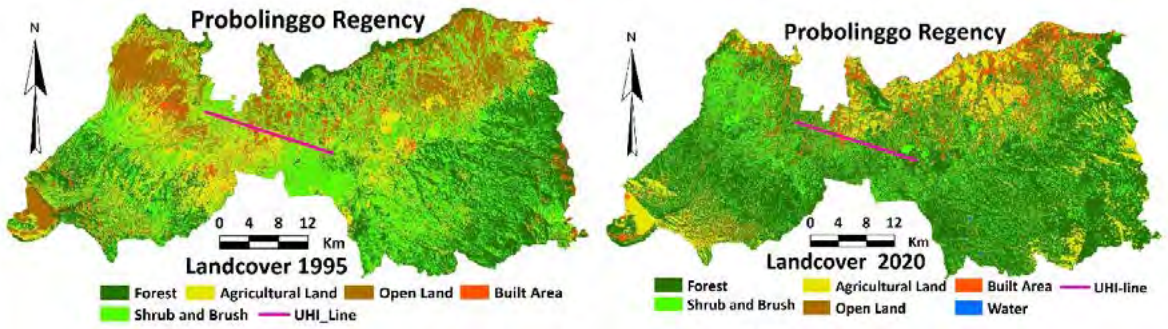

Fig. 5: UHI line of probolinggo regency

Table 3: NDVI along the UHI lines

Research areas	NDVI							
	1995		2001		2015		2020	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Batu City	0.1	0.4	−0.2	0.4	0.0	0.4	0.0	0.5
Malang City	0.0	0.4	−0.3	0.4	0.0	0.5	0.0	0.5
Surabaya City	0.0	0.4	−0.6	0.4	0.0	0.5	0.0	0.5
Malang Regency	0.1	0.4	−0.3	0.5	0.1	0.5	0.1	0.5
Probolinggo Regency	0.1	0.4	−0.3	0.3	0.1	0.5	0.1	0.5
Sampang Regency	0.1	0.4	−0.3	0.3	0.0	0.5	0.0	0.5
Tuban Regency	0.1	0.4	−0.4	0.3	−0.1	0.5	0.0	0.5

Table 4: LST along the UHI lines

Research areas	LST (°C)							
	1995		2001		2015		2020	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Batu City	17.5	26.6	22.1	36.2	20.6	28.0	21.5	28.5
Malang City	19.3	27.5	25.6	35.1	22.7	30.8	22.7	30.0
Surabaya City	20.2	26.7	20.4	33.4	23.5	30.4	22.2	31.4
Malang Regency	19.2	26.2	23.1	32.6	21.1	29.6	22.1	29.7
Probolinggo Regency	22.0	25.4	26.6	33.2	16.9	26.7	23.0	29.7
Sampang Regency	21.9	25.4	24.6	32.5	19.0	29.2	21.7	28.0
Tuban Regency	19.7	25.0	27.8	37.4	23.4	32.9	24.2	36.5

in Table 5. This table shows that all coefficients of regression have a negative value, indicating that NDVI is inversely proportional to LST and this inline with Alexander (2020) and Garouani *et al.* (2021) research results. If the NDVI decreases, then the LST increases and if the percentage of land covered by vegetation decreases, then the LST increases because the area that absorbs the emitted solar energy decreases. This table also shows that nearly all coefficients of determination (or R^2) are >0.5. This finding indicates that the relationship between NDVI and LST is nearly inversely proportional. For Surabaya City, the R^2 values in 1995, 2001, and 2015 are <0.1. This finding indicates that, in Surabaya City, many objects have a small NDVI and do not affect the LST, particularly the objects along the UHI line, such as barren soil, open land, and water.

Relationship between NDVI and NDBI

The built-up area is indicated by the changes of natural land cover to artificial land cover, such as housing, asphalt, concrete, and parking lot. The built-up area can be well detected using Landsat imagery data (Bhatti and Tripathi, 2014). In this study, NDBI was used to analyze the proportion of built-up area and calculated using Eq. 3. The calculated results of

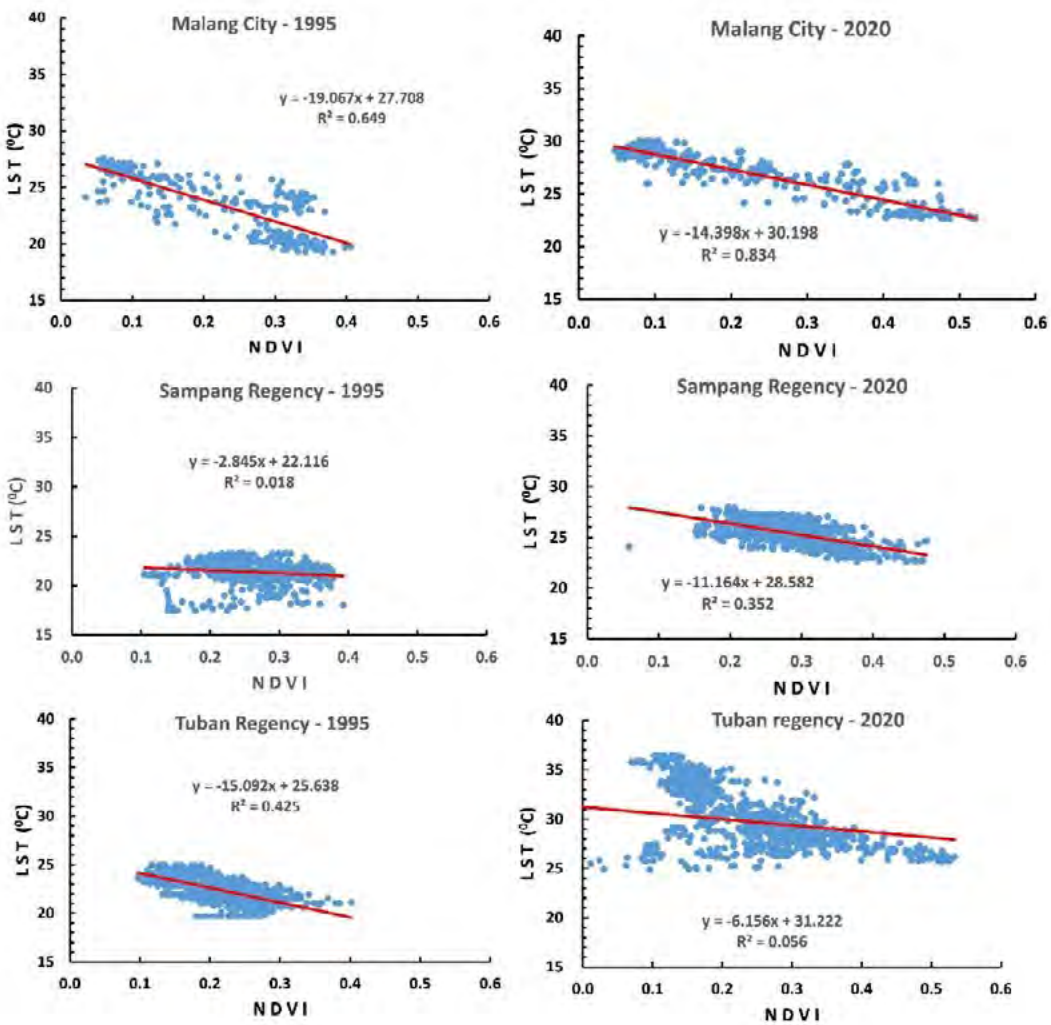

Fig. 6: Relationship between NDVI and LST

NDBI represented by the minimum and maximum values of the entire research area are shown in Table 6. The maximum values of the NDBI of three cities in the research area, i.e., Batu, Malang, and Surabaya, are higher than those of three regencies in the study area, i.e., Probolinggo, Sampang, and Tuban. The maximum value of the NDBI of Malang Regency is higher than those of the three other regencies because Malang Regency is categorized as a developed regency in East Java Province (BPS-SMR, 2021). As mentioned previously, the NDBI indicates the proportion of built-up area, whereas the NDVI indicates the proportion of land covered by vegetation. Urbanization is the change of land covered by vegetation to land covered by manmade materials, such as houses, concrete, and asphalt. Urbanization will extend the built-up area to meet the need for housing, offices, business areas, and accessibility due to population growth. Development of these infrastructures will occupy the land covered by vegetation. The land covered by vegetation will decrease and the land covered by built-up area will be increased. The relationship between NDVI and NDVI should be inversely proportional.

To compare it, the NDBI along the UHI line of each research area needs to be calculated. The calculated results represented by the minimum and maximum values of each research area from 1995 to 2020 are

Table 5: Relationship between NDVI and LST

Research areas	Years	Regression Eq.	Regression coefficient
Batu City	1995	$y = -18.377x + 28.261$	0.489
	2001	$y = -16.583x + 31.938$	0.651
	2015	$y = -13.927x + 29.027$	0.502
	2020	$y = -11.822x + 28.808$	0.479
Malang City	1995	$y = -19.067x + 27.708$	0.649
	2001	$y = -12.218x + 30.492$	0.855
	2015	$y = -15.758x + 30.241$	0.827
	2020	$y = -14.398x + 30.198$	0.834
Surabaya City	1995	$y = -2.714x + 24.301$	0.028
	2001	$y = -2.769x + 28.57$	0.030
	2015	$y = -5.756x + 28.351$	0.092
	2020	$y = -8.421x + 29.647$	0.227
Malang Regency	1995	$y = -4.852x + 23.417$	0.115
	2001	$y = -7.106x + 28.139$	0.413
	2015	$y = -7.093x + 25.954$	0.287
	2020	$y = -9.667x + 27.946$	0.479
Probolinggo Regency	1995	$y = -6.064x + 24.827$	0.342
	2001	$y = -11.581x + 29.773$	0.579
	2015	$y = -20.187x + 28.83$	0.423
	2020	$y = -11.27x + 29.984$	0.600
Sampang Regency	1995	$y = -2.845x + 22.116$	0.018
	2001	$y = -8.294x + 29.74$	0.501
	2015	$y = -6.992x + 28.067$	0.085
	2020	$y = -11.164x + 28.582$	0.352
Tuban Regency	1995	$y = -15.092x + 2.638$	0.425
	2001	$y = -12.681x + 31.462$	0.404
	2015	$y = -10.392x + 30.351$	0.187
	2020	$y = -6.156x + 31.222$	0.056

Table 6: NDBI of the research areas

Research areas	NDBI							
	1995		2001		2015		2020	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Batu City	−0.47	0.41	−0.37	0.48	−0.48	0.26	−0.47	0.25
Malang City	−0.36	0.47	−0.40	0.60	−0.34	0.27	−0.35	0.31
Surabaya City	−0.36	0.45	−0.58	0.58	−0.41	0.30	−0.41	0.36
Malang Regency	−0.65	0.55	−0.56	0.62	−0.45	0.48	−0.46	0.50
Probolinggo Regency	−0.40	0.40	−0.51	0.65	−0.47	0.26	−0.48	0.30
Sampang Regency	−0.41	0.28	−0.70	0.6	−0.48	0.21	−0.47	0.24
Tuban Regency	−0.32	0.25	−0.36	0.58	−0.42	0.60	−0.43	0.41

shown in Table 7. Compared with the minimum value of NDBI of each research area, the minimum value of NDBI along the UHI line is lower because the UHI line is initially drawn from a suburban area to an urban area and finally reaches another suburban area. By drawing a two-dimensional graph of NDVI and NDBI, the relationship between both factors can be represented. Based on the number of research areas and the number of years, a total of 28 NDVI–NDBI graphs are generated. Six of the 28 graphs are shown in Fig. 7 as examples. This figure shows that NDVI is inversely proportional to NDBI. The regression equations of the relationship between NDVI and NDBI for all research areas are shown that all of the coefficients of regression are negative, with more than 50% having values less than −0.7. The results show that 2 areas have coefficients of regression greater than −0.5, 3 areas have coefficients of regression between −0.5 and −0.7, 17 areas have coefficients of regression between −0.7 and −1, and 2 areas have coefficients of regression less than −1. The coefficients of determination of nearly all areas

Table 7: NDBI along the UHI lines

Research areas	NDBI							
	1995		2001		2015		2020	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Batu City	−0.30	0.26	−0.16	0.31	−0.29	0.08	−0.29	0.13
Malang City	−0.36	0.47	−0.10	0.37	−0.31	0.09	−0.34	0.11
Surabaya City	−0.23	0.12	−0.23	0.47	−0.33	0.13	−0.32	0.17
Malang Regency	−0.28	0.27	−0.19	0.34	−0.34	0.09	−0.32	0.10
Probolinggo Regency	−0.23	0.05	−0.09	0.34	−0.31	0.06	−0.36	0.14
Sampang Regency	−0.24	0.06	−0.31	0.37	−0.23	0.05	−0.24	0.10
Tuban Regency	−0.20	0.08	−0.13	0.14	−0.29	0.11	−0.33	0.11

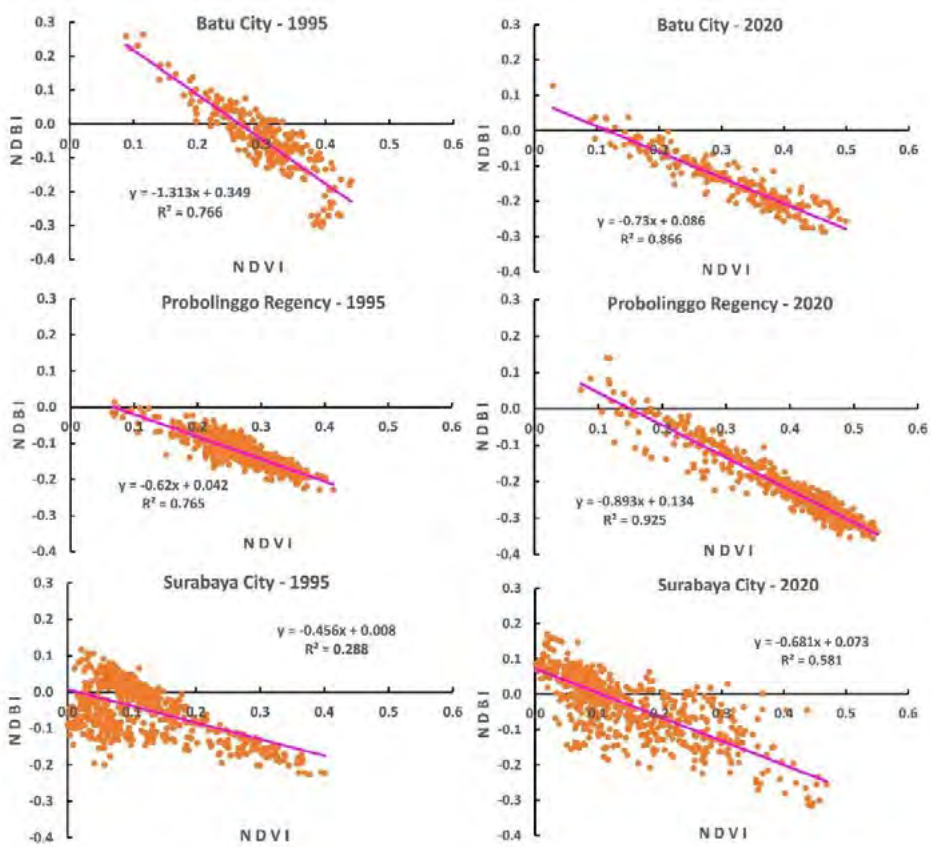

Fig. 7: Relationship between NDVI and NDBI

are >0.5, and only two areas have values <0.5. This finding indicates that NDVI is significantly inversely proportional to NDBI. This result show a clearer relationship quantitatively than the results of Grover and Singh (2015) and Guha *et al.* (2018)'s research. In the same manner, the relationship between NDBI and LST was analyzed.

Fig. 8 shows the graph of the relationship between NDBI and LST in six research areas as an example. The regression analysis results of the relationship between NDBI and LST of the entire research area are shown in Table 8. Table 8 show that NDBI is directly proportional to LST, with a significant coefficient of regression. Among the 28 research areas, 14 areas have a coefficient of determination (R^2) >0.5 and the minimum R^2 is equal to 4.194. This correlation

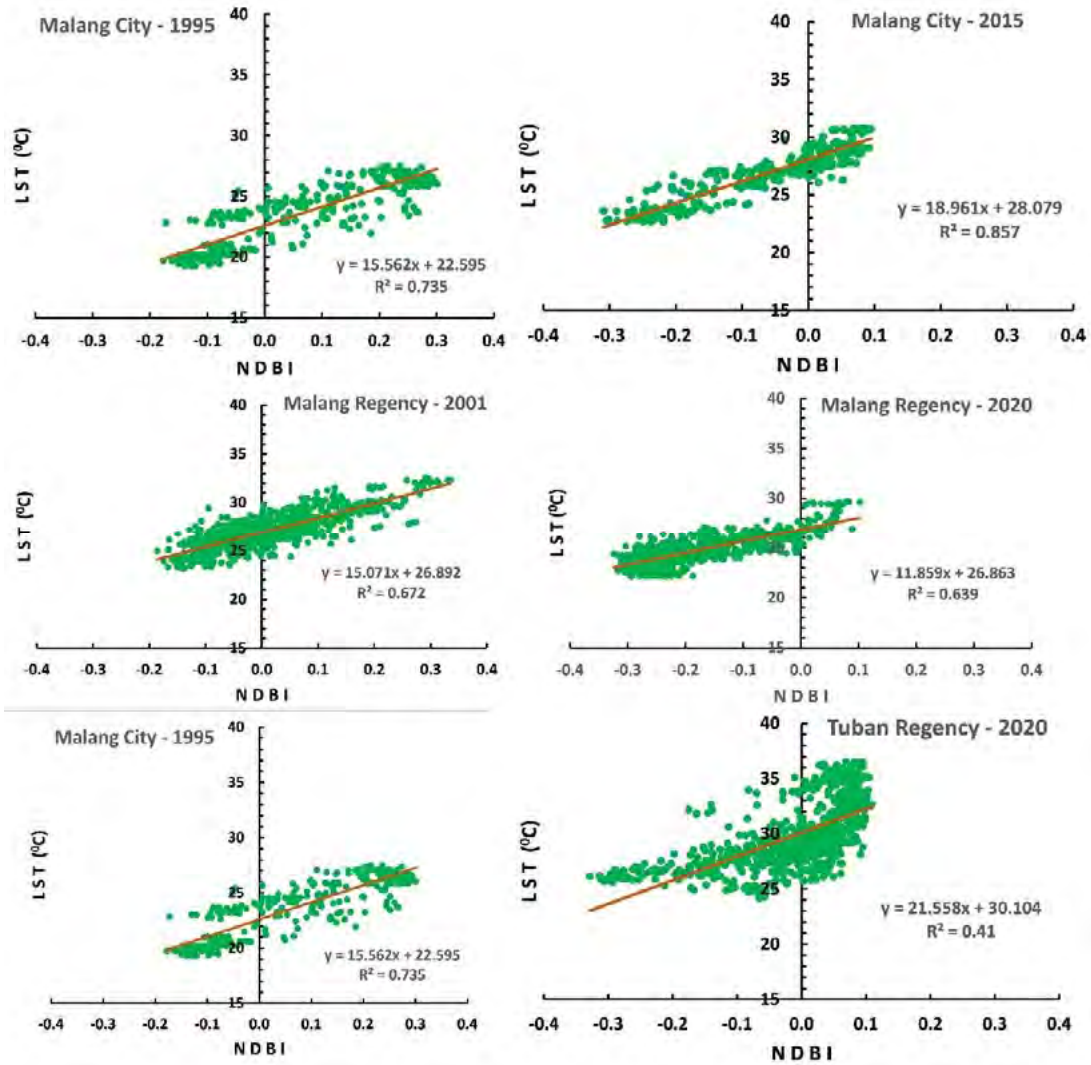

Fig. 8: Relationship between NDBI and LST.

was observed at Surabaya City in 2001, where the development was not yet fully underway. These results show that the relationship between NDBI and LST is clearer than the results of Ibrahim (2017)'s study which was only conducted in one location. Research conducted by Ranagalage *et al.* (2017) resulted in the relationship between urbanization and LST.

Rainfall characteristics

The increase of LST will affect the rainfall characteristics. The relationship between convective precipitation frequency and LST is insignificant (Shiraki and Shigeta, 2013). Meanwhile, Himayoun *et al.* (2020) stated that the increase of LST will intensify precipitation. To verify their statement and to find out the relationship between the two parameters more clearly, the relationship between LST and rainfall characteristics is investigated. The NRD and the average and maximum values of rainfall intensity are considered the rainfall characteristics in this research. The analysis of the relationship between LST and rainfall characteristics was done by comparing the

LST and rainfall characteristics

in each area of the Thiessen polygon for each year. The area of the Thiessen polygon of each

Table 8: Relationship between NDBI and LST

Research areas	Years	Regression Eq.	R^2
Batu City	1995	$y = 14.429x + 23.298$	0.679
	2001	$y = 27.752x + 27.343$	0.762
	2015	$y = 18.285x + 27.306$	0.596
	2020	$y = 16.716x + 27.495$	0.589
Malang City	1995	$y = 15.562x + 22.595$	0.735
	2001	$y = 18.775x + 27.543$	0.823
	2015	$y = 18.961x + 28.079$	0.857
	2020	$y = 16.492x + 27.988$	0.826
Surabaya City	1995	$y = 14.802x + 24.627$	0.601
	2001	$y = 4.194x + 27.143$	0.280
	2015	$y = 11.139x + 28.063$	0.396
	2020	$y = 10.137x + 28.702$	0.263
Malang Regency	1995	$y = 6.825x + 22.739$	0.326
	2001	$y = 15.071x + 26.892$	0.673
	2015	$y = 13.048x + 26.066$	0.548
	2020	$y = 11.859x + 26.863$	0.639
Probolinggo Regency	1995	$y = 10.265x + 24.473$	0.492
	2001	$y = 14.083x + 28.670$	0.417
	2015	$y = 23.852x + 26.646$	0.474
	2020	$y = 11.898x + 28.135$	0.576
Sampang Regency	1995	$y = 9.598x + 21.852$	0.109
	2001	$y = 11.259x + 27.686$	0.777
	2015	$y = 15.651x + 27.336$	0.313
	2020	$y = 10.722x + 25.886$	0.270
Tuban Regency	1995	$y = 15.317x + 22.754$	0.374
	2001	$y = 28.498x + 31.707$	0.365
	2015	$y = 20.631x + 28.799$	0.496
	2020	$y = 21.558x + 30.104$	0.410

research area was drawn based on the number of rainfall stations in each research area. For example, the Probolinggo Regency has 11 rainfall stations. The Thiessen polygon can be drawn based on the locations of the rainfall stations, and the result is shown in Fig. 9. The daily rainfall data are used in this study. The rainfall characteristics of each rainfall station are represented by the average and maximum daily rainfall per year. The rainfall characteristics of Probolinggo Regency from 1995 to 2020 are shown in Table 9.

In case of Probolinggo Regency, the average rainfall intensity during 2015 is higher than 2020, but the maximum rainfall intensity is lower. Due to the Lanina effect, this phenomenon occurs because the rain that occurred in 2020 was not evenly distributed throughout the region like the rain that occurred in 2020. But the maximum rainfall intensity in 2020, will still be higher than in 2015. Based on the Thiessen polygon of Probolinggo Regency, the LST image was cropped, and the average and maximum LST of each area of the Thiessen polygon were calculated. The rainfall characteristics of each rainfall station and the average of maximum LST of each research area in 1995, 2001, 2015, and 2020 of Probolinggo Regency were analyzed based on the Thiessen polygon. The analyses of other research areas were conducted in the same manner. The relationship between LST and rainfall characteristics, especially the average of maximum rainfall intensity and NRD was analyzed. The graph of the relationship between average LST and average of maximum rainfall intensity is shown in Fig. 10. This figure shows that LST is directly proportional to rainfall intensity. However, the coefficient of regression is only equal to 0.1. This finding indicates that the correlation between LST and rainfall intensity is weak but directly proportional. Thus, the increase of LST has a weak relationship with the increase of rainfall intensity. Similarly, the graph of the relationship between LST and NRD is shown in Fig. 10. The graph illustrates that LST has an inverse relationship with NRD or NRD per year. The coefficient of regression is −1.89, and the coefficient of correlation is 0.1. This finding indicates

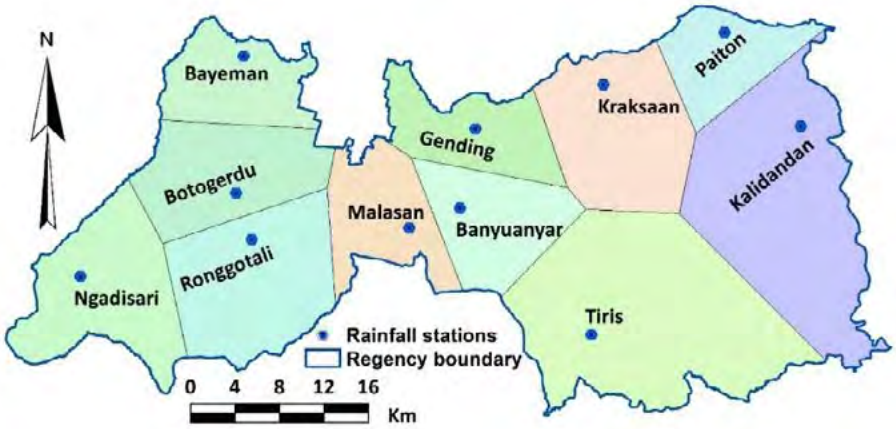

Fig. 9: Thiessen polygon of probolinggo regency

Table 9: Rainfall characteristics of probolinggo regency

No.	Rainfall stations	Rainfall intensity (mm/day)							
		1995		2001		2015		2020	
		Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
1.	Banyuanyar	20.6	95	24.6	92	35.6	110	22.3	135
2.	Bayeman	22.8	121	11.6	54	23.5	120	17.1	109
3.	Botogerdu	22.5	80	24.8	84	35.7	97	25.6	95
4.	Gending	24.3	95	15.3	75	28.9	98	21.6	201
5.	Kalidandan	25.3	92	21.7	89	31.2	148	17.7	110
6.	Kraksaan	24.5	106	30.3	145	19.6	102	22.7	168
7.	Malasan	23.7	102	21.6	87	22.6	165	29.5	215
8.	Ngadisari	17.4	99	24.7	332	14.7	55	17.4	49
9.	Paiton	32.3	188	24.8	158	27.5	89	32.6	140
10.	Ronggotali	20.6	125	23.3	84	30.2	173	33.7	120
11.	Tiris	25.7	80	25.9	87	23.5	164	26.3	185

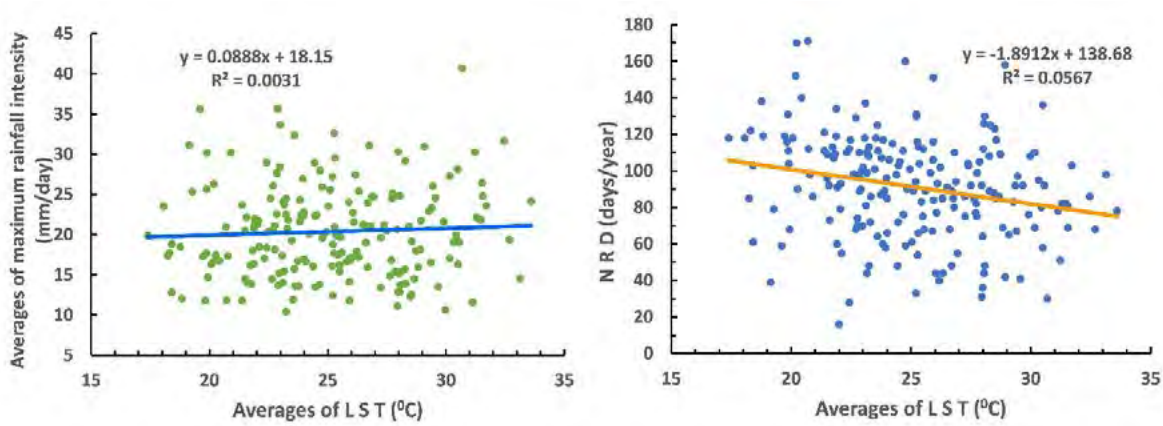

Fig. 10: Relationship between LST and rainfall intensity and LST–NRD

that the correlation between LST and NRD is low with an inverse relationship. Quantitatively, this result is clearer than the research conducted by Garouani *et al.* (2021), Himayoun *et al.* (2020), Hu *et al.* (2020), and Shiraki and Shigeta (2013). The resulting regression equations can be used to estimate the increase in rainfall intensity and decrease in NRD in East Java Province Indonesia caused by decreasing in environmental conditions that cause an increase in LST.

CONCLUSION

In this research, Landsat TM, ETM+, and OLI were used to identify the relationship between NDVI and LST, between NDVI and NDBI, between NDBI and LST, and between LST and rainfall characteristics. Seven areas in East Java Province were used as test areas. The pixel values of NDVI, NDBI, and LST along the UHI line were used to analyze the relationship between NDVI and LST, between NDVI and NDBI, and between NDBI and LST. The UHI line is initially drawn from a suburban area to an urban area and finally reaches another suburban area. Meanwhile, the pixel values generated from the area of the Thiessen polygon were used to analyze the relationship between LST and rainfall characteristics. The analysis results show that NDVI is significantly inversely proportional to LST. All of the coefficients of regression have negative values, and the coefficients of determination (R^2) have values >0.4 in 16 of the 24 research areas. The analysis results of the relationship between NDVI and NDBI show that NDVI is significantly inversely proportional to NDBI. The regression equation for each research area shows that all of the coefficients of regression are negative, with more than 50% having values less than −0.7, and the coefficients of determination are approximately >0.5. This relationship is plausible because NDVI indicates land covered by vegetation and NDBI indicates land covered by manmade materials or built-up areas. The relationship between NDBI and LST was analyzed in the same manner as the relationship between NDVI and LST. The analysis results show that NDBI is significantly directly proportional to LST. The regression equations of all areas show that 14 areas have the minimum coefficient of regression, i.e., equal to 4.194, with R^2 values >0.5. Thus, the increase of the built-up area influences the increase of LST. Finally, the relationship between LST and rainfall characteristics was investigated. The analysis results show that LST has a fairly weak but directly proportional relationship with rainfall intensity, as indicated by the coefficients of regression and determination, both of which are <0.1. Meanwhile, the relationship between LST and the NRD has an inverse relationship, which is also fairly weak, as indicated by a coefficient of regression that is equal to −1.891 and an R^2 that is <0.1. This research shows that LULC change indicated by NDVI and NDBI changes will significantly affect LST. The change of LST will have a fairly weak effect on rainfall intensity and NRD.

AUTHOR CONTRIBUTIONS

A. Suharyanto, the corresponding author has contributed to supervising the fourth and fifth authors in the data analysis NDVI and rainfall analysis, interpreting the results, and preparing the manuscript. A. Maulana helped in the LST and NDBI data analyses. D. Suprayogo designed the analysis of NDVI and LST. Y.P. Devia prepared all the tables and figures and interpretation of the results, especially in NDVI. S. Kurniawan prepared all the maps and interpretation of the relation with rainfall data.

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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
AL	Specific additive rescaling factor
BPS	Badan pusat statistik (Central bureau of statistics)
C	Celsius
DN	Digital number
E	Error correction
Eq.	Equation
ETM+	Enhanced Thematic Mapper+
GIS	Geographic Information System
i.e.	Id est (that is)
J	Joule
K_1	Specific thermal conversion constant 1
K_2	Specific thermal conversion constant 2
K	Kelvin
Km	Kilometer
L5	Landsat 5
L7	Landsat 7
L8	Landsat 8
LST	Land surface temperature
LULC	Land use/land cover
m	Meter
max.	Maximum
min	Minimum
M_L	Specific multiplicative rescaling factor
MTL	Metadata text file extension
NDBI	Normalized Difference Built-up Index
NDVI	Normalized Difference Vegetation Index
N	North
NIR	Near-infrared
NRD	Number of rainfall days
OLI	Operational Land Imager
PV	Proportional vegetation
Q_{cal}	Quantized and calibrated standard product pixel values
s	Second
SWIR	Sort wave infrared
T	Temperature
TC	Temperature Celsius
TIRS	Thermal infrared sensor or Thermal infrared scanner
TM	Thematic Mapper
TOA	Top of atmospheric
UHI	Urban heat island
USGS	United State Geological Survey

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ORIGINAL RESEARCH PAPER

Response surface methodology and adaptive neuro-fuzzy inference system for adsorption of reactive orange 16 by hydrochar

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ABSTRACT

BACKGROUND AND OBJECTIVES: The prediction models, response surface methodology and adaptive neuro-fuzzy inference system are utilized in this study. This study delves into the removal efficiency of reactive orange 16 using hydrochar derived from the *Prosopis juliflora roots*. Hydrochar dose, pH, temperature, and initial reactive orange 16 concentration were studied in batch processes. The correlation coefficients for the batch processes were found to be 0.978 and 0.9999. The results denote that the adaptive neuro-fuzzy inference system predicted the reactive orange 16 removal efficiency more accurately than the response surface methodology model.

METHODS: *Prosopis juliflora roots* roots are converted into hydrochar to remove azo dye from textile waste water. *Prosopis juliflora roots* roots were collected from Ramanad District, Southern Tamil Nadu, India. The moisture content was lowered by drying for 24 hours at 103 degree celcius in an oven with hot air. This biomass was thermally destroyed at 300 degree celcius for 15 minutes without oxygen in an autoclave in a muffle furnace (heating rate: 5 degree celcius per minute). As soon as it reaches room temperature, the hydrochar residue of this biomass was used for adsorption investigations. The batch adsorption process was conducted for 6 hours in a 250 milliliter Erlenmeyer conical flask with a 100 milliliter working volume using an orbital shaker. The pH, dosage, concentration, and temperature are the four parameters chosen for this study to find the maximum removal efficiency of the dye from aqueous solutions. This study validated adaptive neuro-fuzzy inference system, an artificial neural network with a fuzzy inference system, using response surface methodology projected experimental run with Box–Behnken method.

FINDINGS: The adaptive neuro-fuzzy inference system model is created alongside the response surface methodology model to compare experimental outcomes. Experimental data was evaluated using a hybrid least square and gradient technique. Statistical and residual errors assessed experimental and mathematical model correctness. Experimental data matched the adaptive neuro-fuzzy inference system results. Statistical error analysis verified the model's accuracy and precision against experimental data.

CONCLUSION: Response surface methodology and adaptive neuro-fuzzy inference system optimized process conditions. At pH 2, 2 gram per litre hydrochar dosage, 35 degree celcius , and a reactive orange 16 starting concentration of 250 milligram per liter, removal effectiveness reached 86.1 percent. Adaptive neuro-fuzzy inference system predicted higher values than response surface methodology, with batch correlation coefficients of 0.9999 and 0.9997, respectively. Mathematical techniques can accurately estimate dye removal efficiency from aqueous solutions.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
44	10	5

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INTRODUCTION

Oxidation, sand filtration, electrochemical processes, membrane filtration, and precipitation are typical wastewater treatment methods (Gupta *et al.,* 2013). These technologies are ideal in removing suspended solids; other than membrane filtration, removing dissolved solids is difficult. However, membrane filtration is an expensive treatment option and this has led to the development of unique treatment approaches (Hussein *et al.,* 2018; Chinwetkitvanich *et al.,* 2000). Compared with other approaches, one of the best ways to remove pollutants from wastewater is by adsorption (Ghoneim *et al*., 2014) as the removal effectiveness of this process is exceptionally high. Adsorbents, such as clay, silicates, zeolite, lime, and activated carbon, are frequently employed. The widely held adsorbent for the removal of hazardous contaminants is activated carbon (Crini *et al*., 2006; Orshansky *et al*., 1997). However, the production expense of activated carbon is its most significant drawback. One of the most economical methods for removing contaminants is biosorption, which uses inactive or dead microorganisms to create the biosorbent (Kaur *et al*., 2017). Many researchers in the past have made biosorbent from waste compost, neem seeds, moringa seeds, and agricultural biomass (Nayagam and Prasanna, 2022). This biomass is used in the treatment of toxic metals and dyes in wastewater. Hydrochar is created from *Prosopis juliflora roots*, which has high carbon content and several functional groups that promote absorption (Tran *et al*., 2020). The potential of hydrochar depends on the thermal stability of the raw materials sourced in its production. Feedstock is often separated into two groups: wet and dry. Wet biomass is defined as having a moisture percentage of ≥30, whereas dry biomass is defined as having a moisture percentage ≤30. It is usually recommended to use biomass with very low moisture content as the feedstock for the production of hydrochar. This biomass's cellulose, hemicellulose, and lignin content will breakdown during thermal decomposition, and the more stable feedstock will disintegrate at higher temperatures, creating more pores on the surface and increasing the hydrochar's sorption capacity (Wu *et al*., 2008; Beesley *et al*., 2011). Optimizing contaminant removal parameters to reduce experimental trials is a growing issue (Yousif *et al*., 2018). For the purpose of displacing traditional experimental trials, many optimization technologies have been developed. The response surface methodology (RSM) predicts the output using two or more variables with a minimal number of experimental trials (Gopal *et al*., 2014; Deb *et al*., 2019; Ohale *et al*., 2017; Aravind *et al.,* 2015). The adaptive neuro-fuzzy inference system (ANFIS) is a promising optimization technique with the highest correlation coefficient.Complex nonlinear systems can perform better when ANFIS is used (Tejada *et al*., 2021). This study evaluated the use of *P. juliflora roots* in batch procedures for hydrochar synthesis and decolorization of reactive orange 16 (RO 16). *P. juliflora* roots are naturally abundant in Southern India, but its applicability is extremely limited. The functional groups will increase the hydrochar's absorption ability. One of the most used textile dyes is reactive dye. Covalent bonds between the dye and fabric, which have a high binding affinity for cellulose or fabric surface charges, produced this binding (Kumar *et al*., 2019). Aromatic reactive dyes are notoriously difficult to remove (Carneiro *et al*., 2005; Zhang *et al*., 2017). Hydrochar from *P. juliflora* roots was used for the first time to remove RO 16. Hydrochar dosage, solute pH, starting RO 16 concentration, and batch process temperature were optimized in this work. The aim of the study is to compare the experimental data with mathematical modeling to find out the fitting. This study has been carried out in the Environmental Engineering Laboratory of the Department of Civil Engineering, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu, Tamil Nadu, India in 2022.

MATERIALS AND METHODS

P. juliflora roots were collected from Ramanad District, Southern Tamil Nadu, India. The harvested *P. juliflora* roots were allowed to naturally dry for seven days before being shredded to particle size 7.5 mm. Biomass moisture content was lowered by drying for 24 h at 103°C in an oven with hot air. In addition, this thermal biomass was destroyed at 300°C for 15 min without oxygen in an autoclave in a muffle furnace (heating rate: 5°C per minute). As soon as it reaches room temperature, the so-called hydrochar residue of this biomass was employed for adsorption investigations. In our study, hydrochar was utilized in its unmodified state (Chai *et al*., 2021). Sigma-Aldrich, India, supplied all of the compounds employed in the current experiment, including RO 16.

$C_{20}H_{17}N_3Na_2O_{11}S_3$ was the empirical formula, 617.54 g/mol was the molecular weight, and 388 nm was the wavelength of RO 16 (Kaminski *et al*., 2015).

Batch study

The batch adsorption process was run for 6 h in 250 mL conical flask with a 100-mL toiling volume using an orbital shaker. For a thorough fusing of the sorbent and dye molecules, the orbital shaker was run at 180 rpm. Following the batch trials, 5 cc of the sample was centrifuged at 1800 rpm for 5 min. Lastly, an ultra violet visible spectrophotometer was utilized to determine the sample's ultimate concentration. Eqs. 1 and 2 are used to calculate the removal efficiency in the dye (Lenin *et al*., 2021).

$$\text{Removal efficiency} = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (1)$$

$$\text{Total dye removal}(\%) = \frac{m_{\text{adsor}}}{m_{\text{total}}} \times 100 \quad (2)$$

Where;

V: dye treatment volume (L)

Co: pre-adsorption concentration (mg/L)

Ce: adsorption concentration (mg/L)

Design of experiments

RSM

Minitab was used to implement Box–Behnken experimental design in response surface approach. The batch process input parameters were temperature, pH hydrochar dose, and initial RO 16 concentration. Table 1 presents a summary of the variable's many levels. Eq. 4 illustrates the RSM-developed quadratic model (Lenin *et al*., 2021).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{K} \beta_{ii} x_i^2 + \sum_{i=1} 0 \sum_{j=i+1} \left(\beta_{ij} x_i x_{ij} + \grave{o}\right) \quad (4)$$

Where;

Y: Response (% removal efficiency),

β0, βi, βii, and βij: intercept, quadratic, linear and interaction effects

xi, xj: independent variables

ε: error.

ANFIS

ANFIS is regarded as one of the most guaranteed technologies for predicting nonlinear complex systems (Del Cerro *et al*., 2021). The present study validated ANFIS using RSM's projected experimental run. In batch experiments, a total of 31 experimental trials were used to predict clearance efficiency. The predictive model is built on the first-order Sugeno, and the resulting model for batch processes is shown in Fig. 1. ANFIS contains five layers: one input, one output, and three layers (fuzzification, logical rule, and defuzzification). Hydrochar dose, initial RO 16 concentration, pH, and temperature are the batch process inputs. The output layer for batch operations consists of a single output termed removal efficiency,

Table 1: Coded variables

Term	Coef.	SE Coef.	t-value	p-value	VIF
Constant	67.89	6.77	10.02	0.000	-
Dosage	4.05	3.66	1.11	0.285	1.00
pH	−1.58	3.66	−0.43	0.671	1.00
Initial concentration	−3.72	3.66	−1.02	0.325	1.00
Temperature	−3.72	3.66	−1.02	0.325	1.00
Dosage*dosage	0.66	3.35	0.20	0.846	1.03
pH*pH	2.06	3.35	0.61	0.548	1.03
Initial concentration*initial concentration	2.85	3.35	0.85	0.407	1.03
Temperature*temperature	2.64	3.35	0.79	0.443	1.03
Dosage*pH	2.02	4.48	0.45	0.658	1.00
Dosage*initial concentration	0.66	4.48	0.15	0.885	1.00
Dosage*temperature	−2.02	4.48	−0.45	0.658	1.00
pH*initial concentration	2.02	4.48	0.45	0.658	1.00
pH*temperature	−0.66	4.48	−0.15	0.885	1.00
Initial concentration*temperature	−2.02	4.48	−0.45	0.658	1.00

(*VIF – Variance inflation factor)

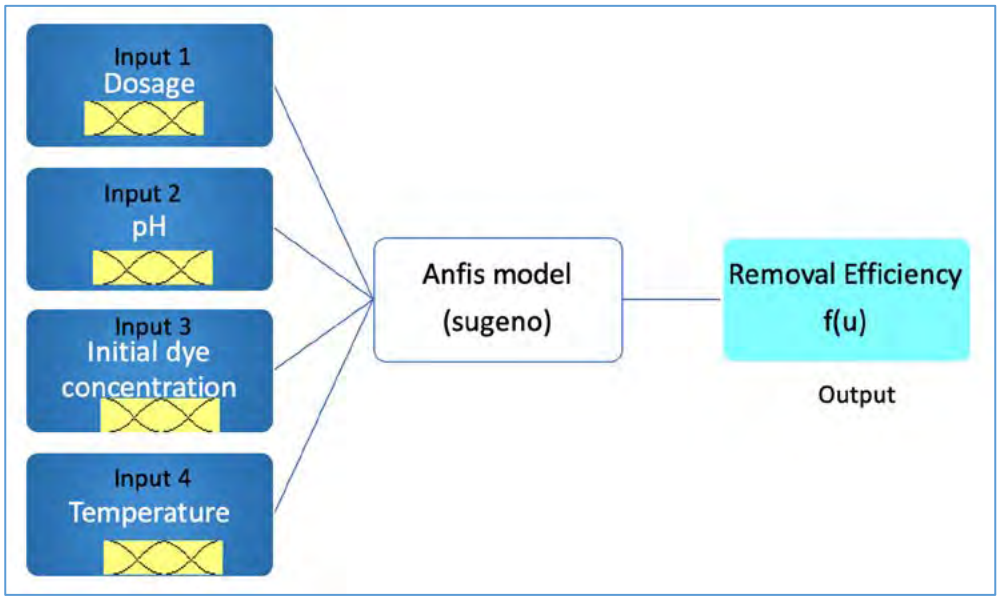

Fig. 1: ANFIS model for batch study

output membership function is the sum total of all incoming signals. Removal efficiency will result from combining these signals. The three hidden layers are membership function, logical rule, and output membership function for output prediction (Zaghloul *et al*., 2020).

Statistical error analysis

Analysis done using Eqs. 5–10 to find the model that closely resembled the experimental data (HYBRID) (Lenin *et al*., 2021).

$$\mathrm{HYBRID}(\%) = \frac{1}{N-P}\sum\left[\frac{\left(Q_{\exp,i}-Q_{\mathrm{cal},i}\right)^2}{Q_{\mathrm{cal},i}}\right]\times 100 \quad (5)$$

Average relative error (ARE)

$$\mathrm{ARE}(\%) = \frac{100}{N}\sum_{i=1}^{N}\left[\frac{\left|Q_{\exp,i}-Q_{\mathrm{cal},i}\right|}{Q_{\exp,i}}\right] \quad (6)$$

Marquardt's percent standard error deviation (MPSED)

$$\mathrm{MPSED}(\%) = \sqrt{\frac{\sum\left(\frac{Q_{\exp,}-Q_{\mathrm{cal},}}{Q_{\exp,i}}\right)^2}{N-P}}\times 100 \quad (7)$$

Absolute average relative error (AARE) (Zaghloul *et al*., 2020)

$$\mathrm{AARE} = \frac{1}{N}\sum_{i=1}^{N}\left(\left|\frac{Q_{\exp,i}-Q_{\mathrm{cal},i}}{Q_{\exp,i}}\right|\right) \quad (8)$$

Adjusted R^2

$$\mathrm{Adj}R^2 = 1-\left[\left(1-R^2\right)*\frac{(N-1)}{(N-P-2)}\right] \quad (9)$$

Root mean square error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Q_{\exp,i}Q_{\mathrm{cal},i}}{Q_{\exp,i}}\right)^2} \quad (10)$$

Where,

N:number of experiments,

P: factors.

Qexp,i: obtained values

Qcal,i: Model predictions.

RESULTS AND DISCUSSION

RSM for batch study

The RSM model examined linear, quadratic, and two-way variable interactions using a Box–Behnken

experimental design. The accuracy of the created model using experimental data was projected using the correlation coefficient with the highest value and the error with the lowest value. A correlation coefficient (R^2) of 0.9978 was attained with little error. This points to the fact that the derived model was highly connected with experimental data (Jaafaria *et al*., 2019). In addition, the adjusted R^2 was determined to be 0.9974, and the difference between R^2 and adj R^2 was calculated to be 0.0007, confirming adj R^2 was identical to R^2 and emphasizing the model's high significance. The adjusted R^2 was employed in the model to calculate the variance of the mean. The small difference between R^2 and adj R^2 suggests that the model's mean value is correct and that no mistake was concomitant with model terms, experimental data, or predicted data (Taran and Aghaie, 2015). The quadratic equation produced by the RSM model for calculating removal efficiency (%) is shown in Eq. 11.

$$\text{Removal efficiency}=96.1 + 0.4(A) - 5.50(B) - 0.215(C) - 0.114(D) + 0.42(A^2) + 0.330(B^2) + 0.000730(C^2) + 0.00188(D^2) + 0.65(A*B) + 0.0084(A*C) - 0.0432 (A*D) + 0.0129(B*C) - 0.0070(B*D) - 0.00086(C*D) \quad (11)$$

*A – Dosage, B – pH, C – Initial concentration, D – Temperature

The linear, quadratic, and two-way interaction models' analysis of variance is shown in Table 2. At 95% confidence, P values >0.05 are insignificant (Sodeifian *et al*., 2015). Fisher's F-value calculates the mean square error sum/residual error ratio to assess model and input parameter relevance. More relevant models have higher F-values (Yan *et al*., 2014). The model's F and P values were 372 and 0.000001, respectively, suggesting its importance. The model also showed that linear and quadratic components were significant, but two-way interactions were not (Kamyab *et al.,* 2022).

Diagnostic plots for batch study

Pareto charts and residual analysis were used to evaluate the model's relevance, which was calculated via the Pareto chart. The model produced a 2.18 t-value with 14° of freedom and 95% confidence (=0.05). Significant factors have t values >2.18. Table 2 shows that quadratic and two-way interactions are weak because linear component D (temperature) has minimal effect. Hydrochar dosage, pH, and starting RO 16 concentration affect linear and quadratic models. The Pareto analysis showed hydrochar dose and solute pH significantly affected RO 16 removal efficiency. Hydrochar dosage and solute pH exhibited the highest t-test values, 52.53 and 31.92, respectively. Fig. 3 shows

Table 2: Analysis of variance (ANOVA) for batch adsorption process

Source	DF	Adj SS	Adj MS	f-value	p-value	Remarks
Model	14	1851.11	132.222	0.41	0.000	Significant
Linear	4	1116.63	279.159	0.87	0.000	Significant
Dosage	1	392.87	392.871	1.22	0.000	Significant
pH	1	60.25	60.246	0.19	0.000	Significant
Initial concentration	1	331.82	331.824	1.03	0.000	Significant
Temperature	1	331.69	331.694	1.03	0.000	Significant
Square	4	458.67	114.668	0.36	0.835	
Dosage*dosage	1	12.47	12.469	0.04	0.000	Significant
pH*pH	1	121.30	121.297	0.38	0.000	Significant
Initial concentration*initial Concentration	1	232.60	232.605	0.72	0.000	Significant
Temperature*Temperature	1	198.93	198.928	0.62	0.000	Significant
2-Way Interaction	6	275.80	45.967	0.14	0.988	
Dosage*pH	1	65.51	65.509	0.20	0.658	
Dosage*initial concentration	1	6.88	6.884	0.02	0.885	
Dosage*temperature	1	65.51	65.509	0.20	0.658	
pH*initial concentration	1	65.51	65.509	0.20	0.658	
pH*temperature	1	6.88	6.884	0.02	0.885	
Initial concentration*temperature	1	65.51	65.509	0.20	0.658	
Error	16	0.16	0.138			
Lack-of-Fit	10	0.16	0.16	*	*	Significant
Pure error	6	0.000	0.000			
Total	30	6991.67				

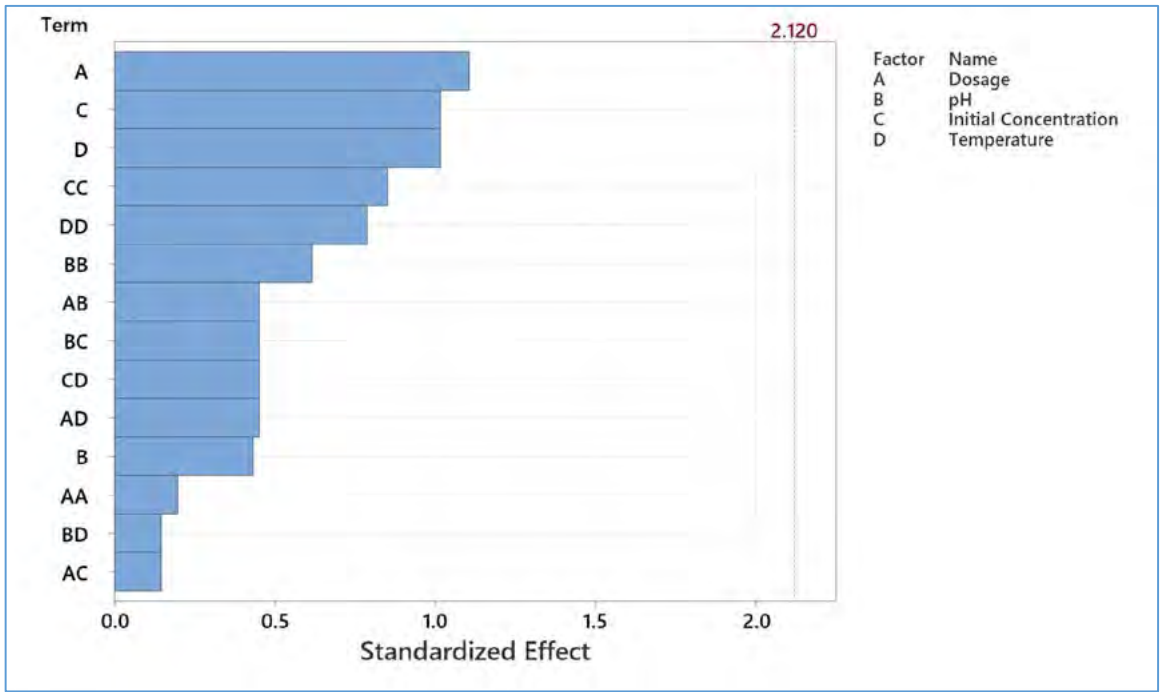

Fig. 2: Pareto chart analysis for removal efficiency

projected and actual residual error and probability graphs. Predicted values matched experimental values with a little residual error (Ahmad *et al*., 2009).

Hydrochar dosage and solute pH also affected RO 16 removal efficiency, according to the Pareto analysis in Fig. 2. The maximal t-test values for hydrochar dosage and solute pH were 52.53 and 31.92, respectively. Fig. 3 shows predicted and actual residual error and probability graphs. Predicted values matched experimental values with a minor residual error. Interpretations had a residual error ranging from +0.7 to −0.7, with observation 8 exhibiting the largest residual error of 0.7 (Xin hui *et al*., 2012).

Individual effects and interaction plots for batch study

Fig. 4 displays the effect of the influencing variables and interaction graphs. Removal effectiveness rose with an increase in hydrochar dosage, dropped with a rise in pH, declined with an increase in starting RO 16 concentration, decreased when the temperature was raised, and increased when the temperature was raised to 40°C, as shown in Fig. 4. As temperature rises, the sorbent may develop driving forces, speeding dye molecules toward it and boosting sorption. When pH rose from 2 to 4, the mean value dropped from 82.81% to 71.49%. This would be performed at a higher pH by connecting positively charged protonated hydrogen ions to the surface of the hydrochar, attracting negatively charged reactive dyes (Munagapati *et al*., 2017). Fig. 5 shows the interaction plots for removal efficiency .The removal efficacy improved as the hydrochar dosage increased, perhaps due to the existence of more binding sites at higher concentrations, resulting in enhanced adsorption capacity. The limited surface area is insufficient to absorb all of the dye molecules at a lower dosage (Aksu and Zümriye, 2005). Figs. 5 and 6 show the interactions between factors at different levels, as well as a matrix plot for a batch study.

Response optimizer for batch study

Fig. 6 shows the response optimizer improving removal efficacy. With an optimizer accuracy of 1, removal efficacy went from 86.1% to 88.12%. Ideal conditions were 2.6 g/L hydrochar, solute pH of 2, 250 mg/L RO 16, and a temperature of 38°C. Three sets of batch experiments were done under ideal settings to measure removal efficacy, and the results indicated an average removal rate of 87.92%.

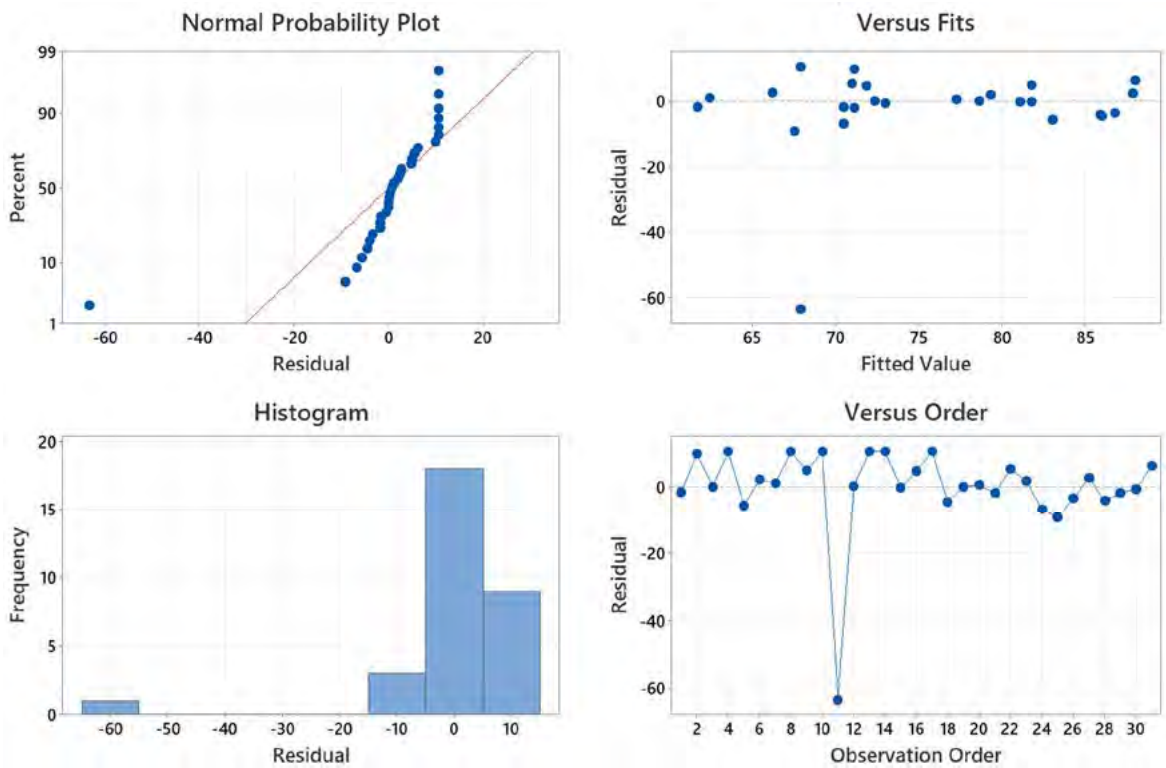

Fig. 3: Residual plots for removal efficiency

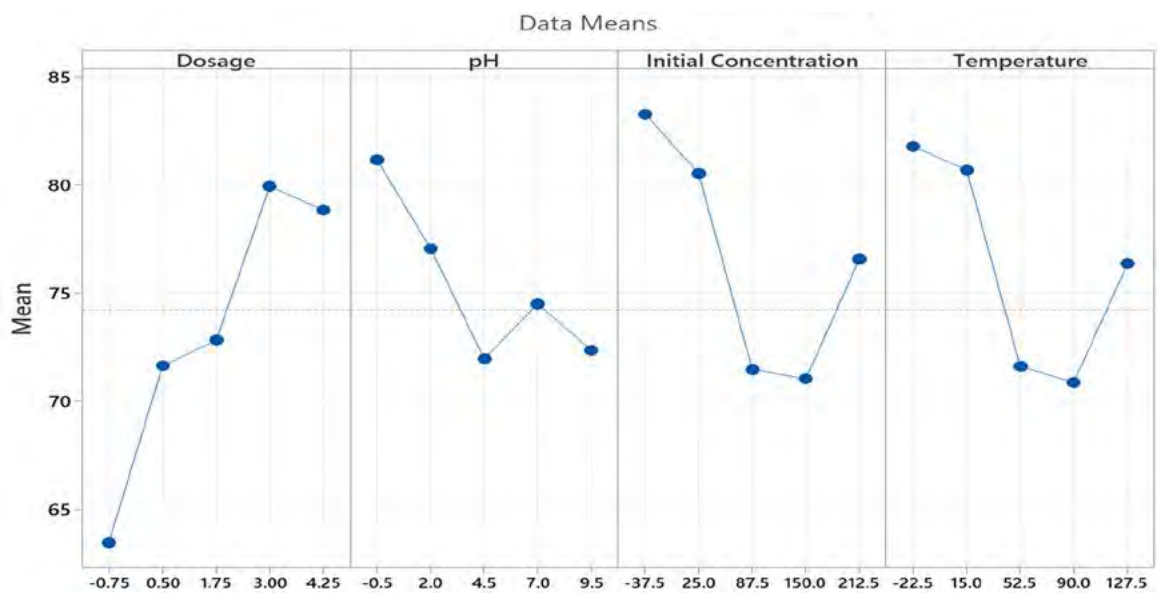

Fig. 4: Main effect plots

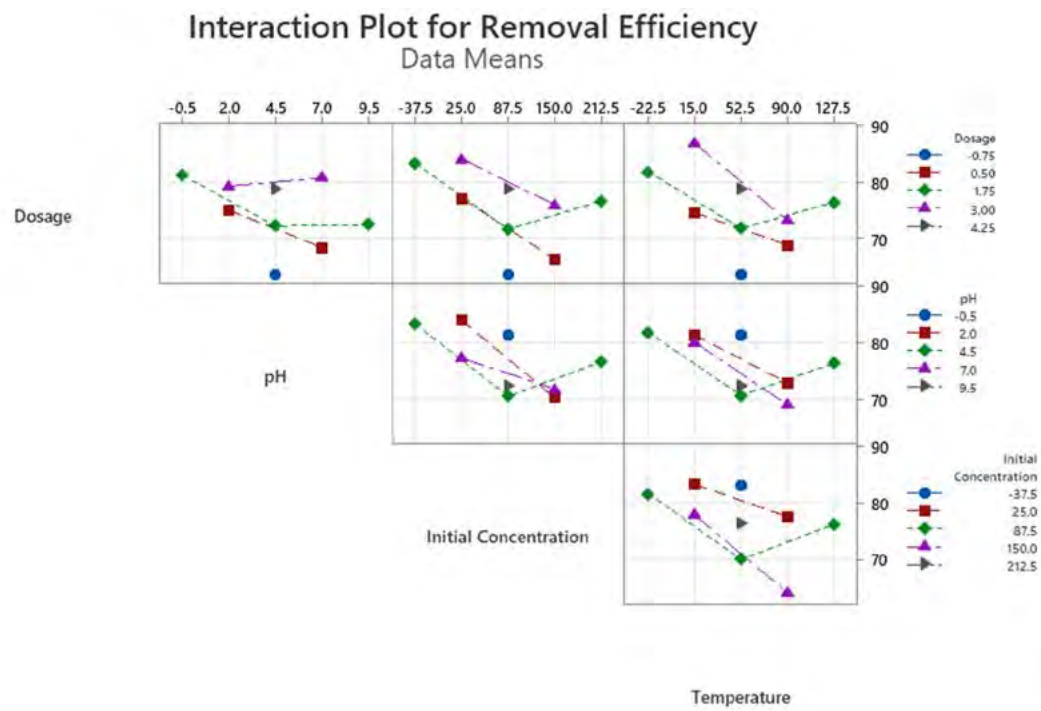

Fig. 5: Interaction plots for removal efficiency

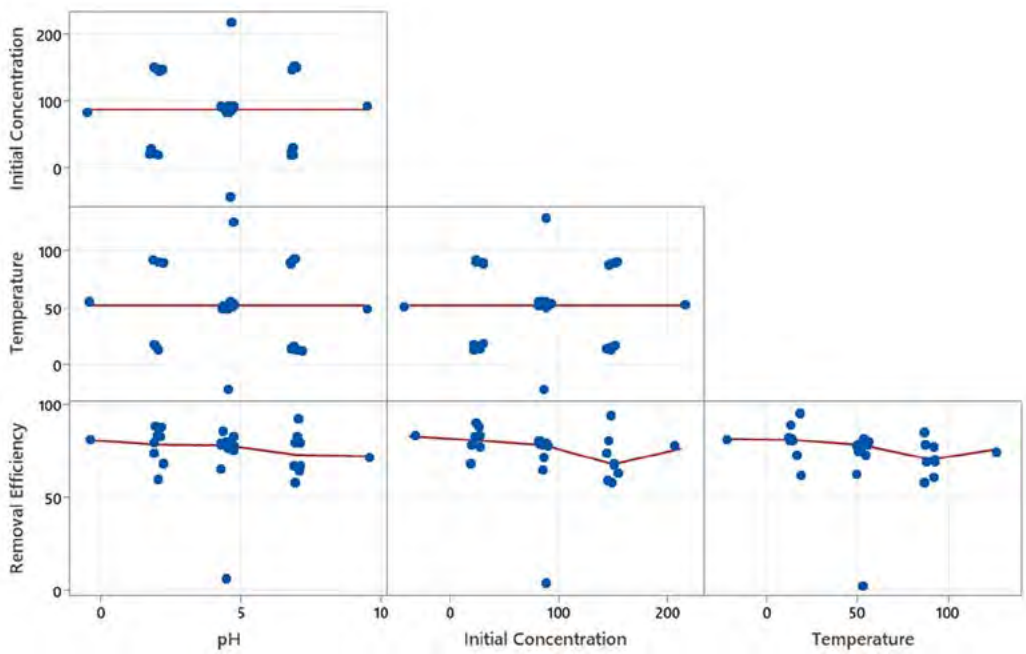

Fig. 6: Matrix plot

ANFIS for batch study

Experimental data were evaluated using a hybrid least square and gradient technique. Fig. 7 shows a grid partitioned Sugeno-type structural model for removal efficacy assessment. Four input variables were utilized to produce a single output, with low, medium, and high membership functions applied to each. With minor errors, a correlation coefficient of 0.9999 between the experimental and projected values reveals that the model best matches the experimental data. ANFIS trains data using fuzzy inference with multiple hidden neural networks, which reduces errors and improves model accuracy. Epoch 3 has a 0.000075 mean square error. This points toward the model's accuracy in predicting RO 16 elimination efficiency. Table 3 contains a detailed description of the expected removal efficiency for each trial (Ghorbani *et al*., 2016). A surface map was also constructed to better understand the interaction between the input variables, as seen in Fig. 8. As shown in Fig. 8, removal efficiency improved when the hydrochar dosage was increased, the pH was dropped, the starting RO 16 concentration was decreased, and the temperature was reduced from 30°C to 35°C, with a further temperature rise to 40°C, boosting removal efficacy. Fig. 8a, for example, demonstrates the relationship between hydrochar dosage (A) and pH (B) in terms of removal efficiency. The removal effectiveness improved as the hydrochar dosage increased from 1 to 3 g/L, but decreased when the pH increased from 2 to 4. The highest removal effectiveness of 85.6% was observed with a hydrochar dosage of 3 g/L and pH 2.

Statistical and residual errors assessed experimental, RSM, and ANFIS correctness. Table 3 demonstrates experimental, RSM, and ANFIS elimination effectiveness at different levels of residual errors for each model. At pH 2, 2 g/L hydrochar, 500 mg/L RO 16, and 35°C, 86.1% removal was achieved. Under identical process settings, RSM and ANFIS removed 86.3% and 86.1%, respectively. The findings show that RSM and ANFIS projected values match real data, and the residual error between experimental and model data is minimized. RSM correlated 0.978 and ANFIS 0.9999. ANFIS data matched experimental data better than RSM, with reduced residual error. The RSM correlation coefficient was 0.978 (Zaghloul *et al*., 2020).

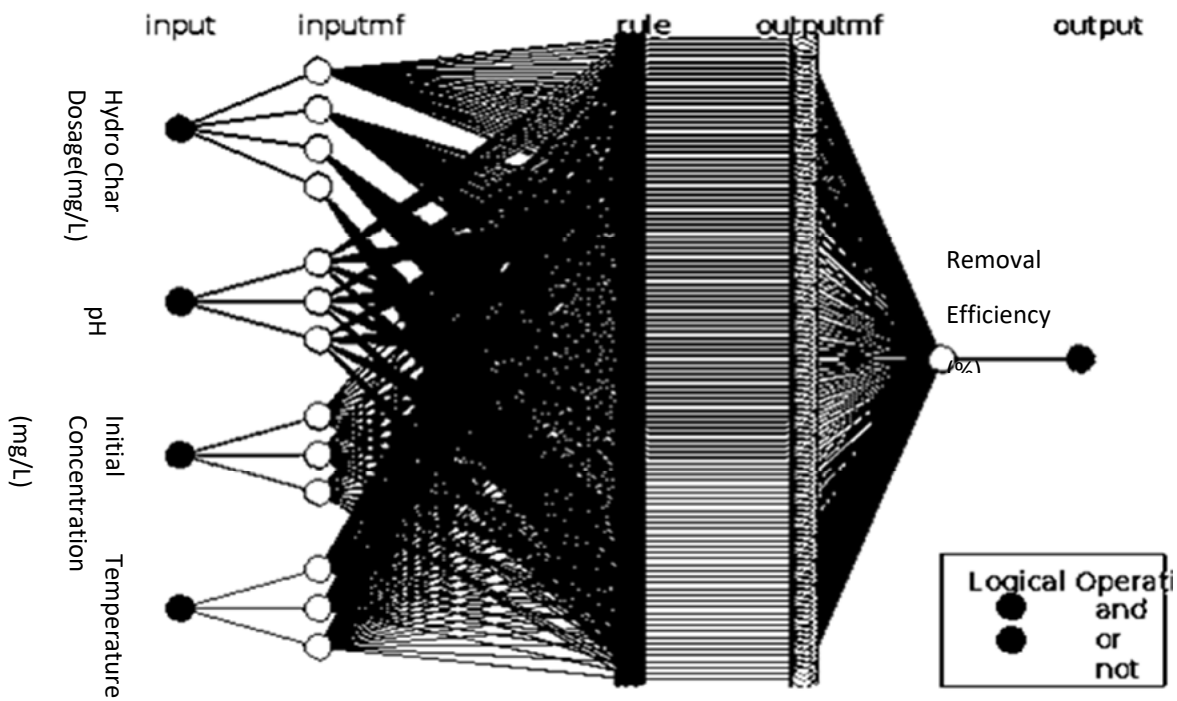

Fig. 7: ANFIS for batch study

Table 3: Removal efficiency of experimental, RSM and ANFIS models for batch study

Dosage	pH	Initial concentration	Temperature	Removal efficiency	RSM	ANFIS
0.5	7	150	90	60.065	60.2	60.1
0.5	7	25	15	81.0075	81.3	81.2
0.5	2	150	15	72.415	72.7	72.6
1.75	4.5	87.5	52.5	78.45875	78.8	78.8
0.5	2	25	90	77.4575	77.5	77.3
3	2	25	15	90.1975	90.4	90.6
0.75	4.5	87.5	52.5	63.49	63.8	63.5
1.75	4.5	87.5	52.5	78.45875	78.7	78.9
3	2	25	90	86.6475	86.8	86.3
1.75	4.5	87.5	52.5	78.45875	78.9	78.8
1.75	4.5	87.5	52.5	4.5	4.6	4.7
4.25	4.5	87.5	52.5	78.83375	78.9	78.8
1.75	4.5	87.5	52.5	78.45875	78.6	78.4
1.75	4.5	87.5	52.5	78.45	78.7	78.5
3	2	150	15	81.605	81.8	81.6
1.75	4.5	212.5	52.5	76.58	76.7	76.6
1.75	4.5	87.5	52.5	78.45875	78.6	78.7
3	7	25	15	81.3975	81.5	81.4
0.5	2	25	15	81.0075	81.1	81.4
3	7	25	90	77.8475	77.9	77.7
0.5	7	25	90	68.6575	68.7	68.8
1.75	4.5	87.5	52.5	76.35875	76.5	76.4
1.75	0.5	87.5	52.5	81.15875	81.4	81.3
0.5	7	150	15	63.615	63.7	63.5
3	2	150	90	58.315	58.4	58.7
1.75	4.5	-37.5	52.5	83.2775	83.3	83.4
0.5	2	150	90	68.865	68.9	68.9
1.75	4.5	87.5	22.5	81.7825	81.8	81.9
3	7	150	90	69.255	69.4	69.3
1.75	9.5	87.5	52.5	72.35875	72.5	72.4
3	7	150	15	94.24	94.6	94.6

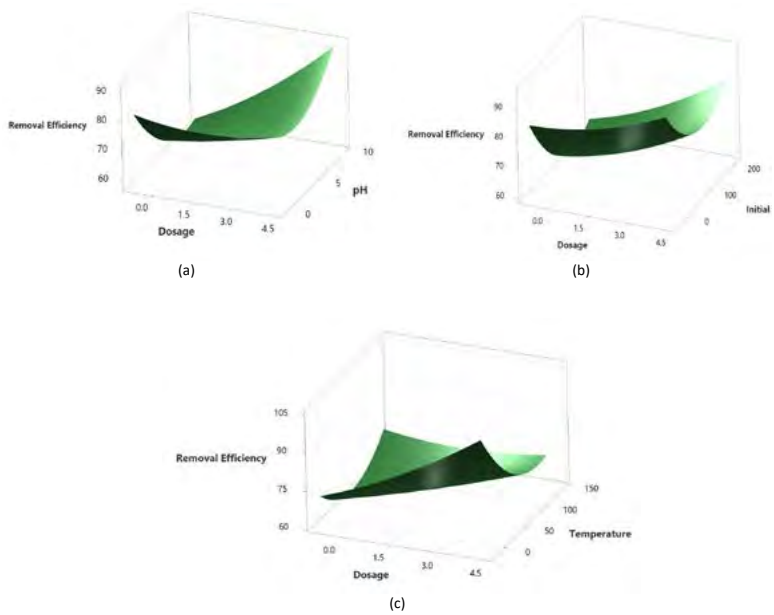

Fig. 8: (a) Surface plot of removal efficiency vs, pH, dosage,(b) Surface plot of removal efficiency vs. initial concentration, dosage (c) Surface plot of removal efficiency vs. temperature, dosage

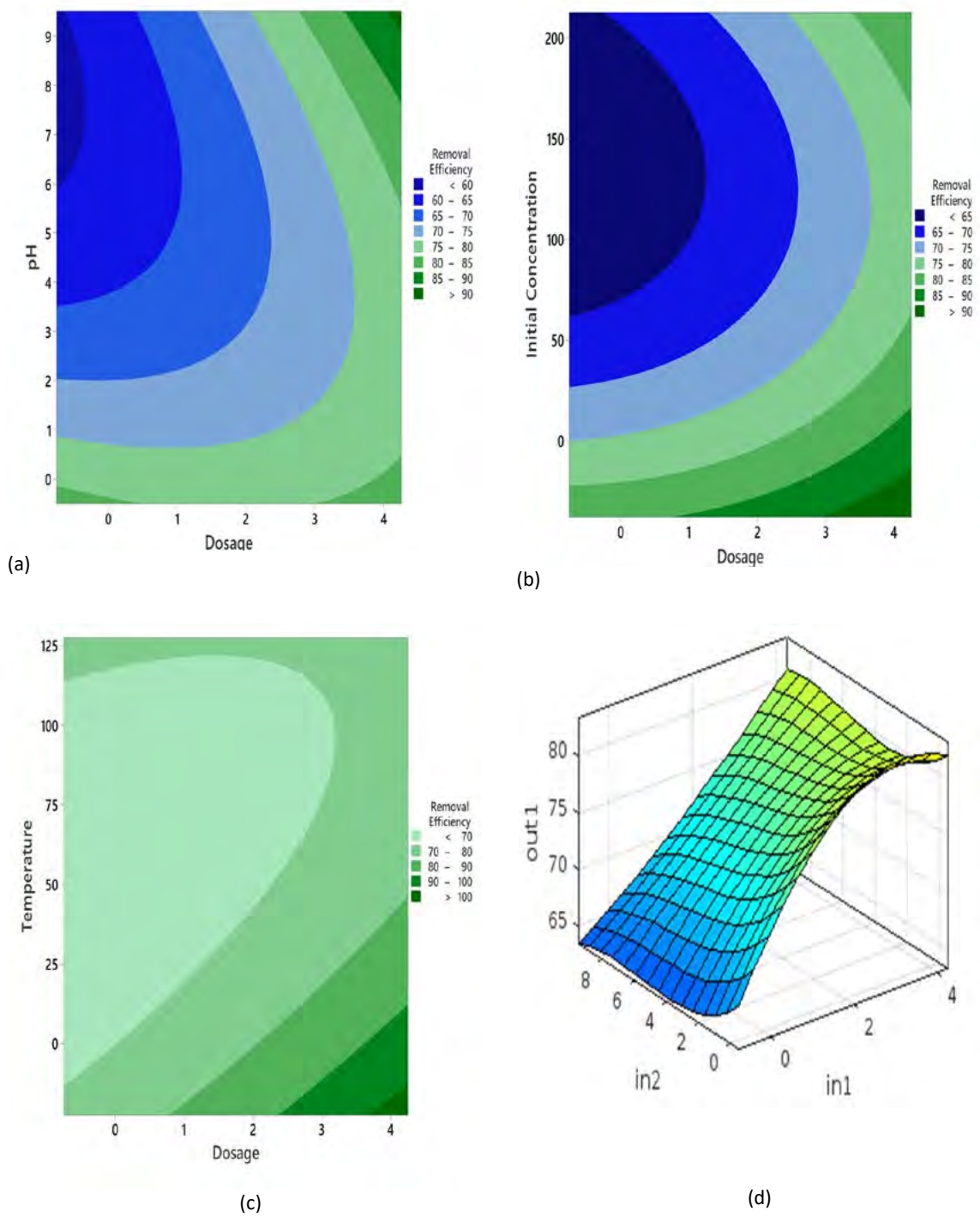

Fig. 9: (a) Contour plot of removal efficiency vs pH, dosage (b) Contour plot of removal efficiency vs initial concentration, dosage (c) Contour plot of removal efficiency vs. temperature, dosage (d) ANFIS surface plot for batch study

Fig. 10:

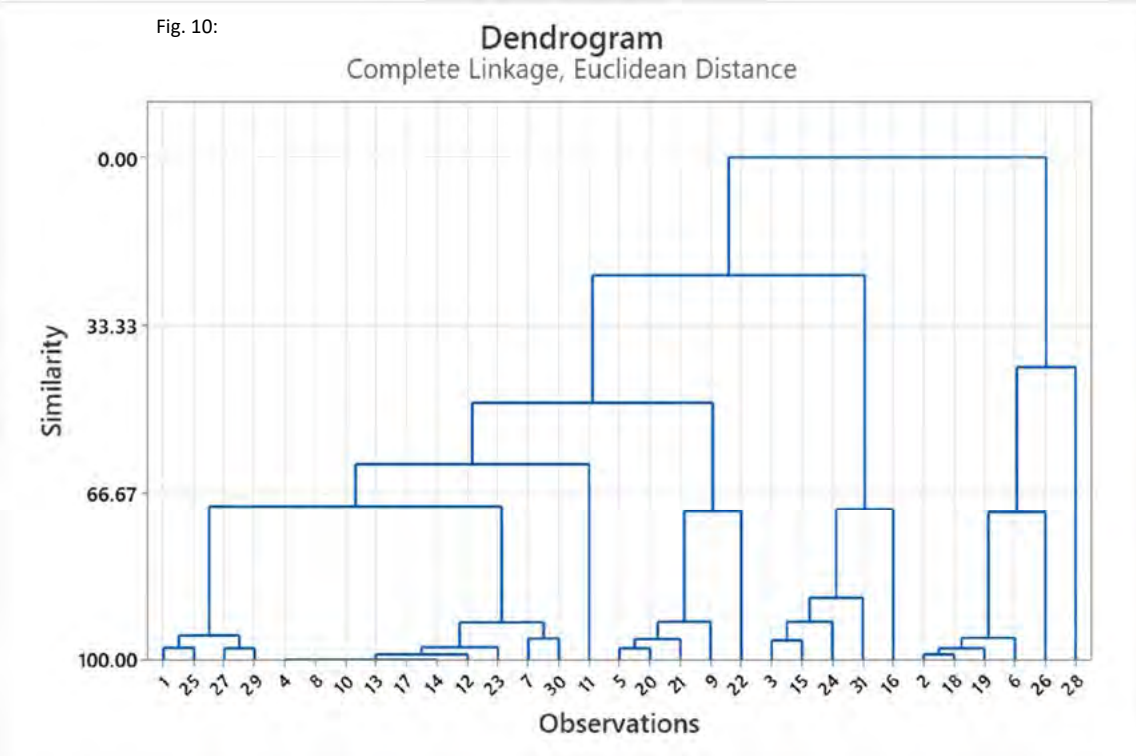

Fig. 10: Cluster analysis

Table 4: Statistical error analysis

S.No	Error function	RSM	ANFIS
1	AARE	0.00003	0.00002
2	HYBRID	0.0015	0.00019
3	ARE	0.00125	0.00048
4	MPSED	0.00758	0.00285
5	RMSE	0.00009	0.00005
6	Adj R^2	0.9981	0.9999
7	R^2	0.9988	0.9999

Dosage Variable cluster analysis compares experimental variables with RSM and ANFIS in Fig. 10. It shows an experimental and RSM cluster with 99.99 similarity and zero distance. Experimental and RSM data created the second cluster with a similarity of 99.94 and a distance of 0.001. Experimental data matched ANFIS results.

Statistical Error analysis verified the model's accuracy and precision against experimental data. Table 4 shows experimental, RSM, and ANFIS model statistical errors. It shows that both models had insignificant errors, and the RSM and ANFIS correlation coefficients were 0.9988 and 0.9999, respectively. The present correlation coefficient is extremely high and confirms the model's fit, according to Joglekar and May (Lenin *et al*., 2021). To determine if RSM and ANFIS were overpredicted, the corrected R^2 was 0.9988 and 0.9999, respectively. These findings demonstrated that the model's predicted values match the experimental data. The fact that the ANFIS model outperformed the RSM model was proved by the fact that the ANFIS model had a higher correlation coefficient and fewer mistakes. adj R^2 was 0.9981 and 0.9999. The model's ANOVA shows that the difference between R^2 and adj R^2 was 0.0011 and <0.1, proving its

Table 5: Overview of work carried out using RSM

Anaerobic reactor	Type of pollutant	Method	Runs	Dependant variables	Independent variables
Batch reactor (Kainthola *et al*., 2018)	Rice straw hydrilla verticillata	CCD	20	C/N ratio, F/M ratio, pH	methane yield
Hybrid bioreactor (Mortezaei *et al*., 2018)	Yogurt effluent	CCD	19	COD influent	HRT
Batch reactor (Safari *et al*., 2018)	Cattle manure and canola residues	Box–Behnken	29	Temperature	Stirring time
MASBR (Rajasimman *et al.,* 2017)	Textile waste water	CCD	13	Sorbent dosage	Biomass support
Batch reactor (Jacob S *et al.,* 2016)	Potato waste and aquatic weed	CCD	20	Total solid, Proportion of co-support, Inoculum concentration	Methane yield
Floating drum anaerobic digester (Sathish and Vivekanandan *et al*., 2016)	Rice straw	CCD	30	Temperature, pH, Substrate concentration	Biogas yield
Mixed plug-flow reactor (Rasouli *et al*., 2015)	Cow manure	CCD	18	OLR, Temperature, Mixing level	Biogas Production, Methane yield
Batch reactor (Sajeena *et al.,* 2014)	Organic fraction municipal solid waste	CCD	20	pH, Substrate concentration, TOC	Biogas production
Batch and Column reactor (Lenin *et al.,*2021)	Reactive Red 120 dye	Box–Behnken	27	Dosage, pH, Concentration, Temperature,bed depth,flow rate	Removal Efficiency
This study	Reactive orange 16 dye	Box Behnken	31	Dosage, pH, Concentration, Temperature	Removal Efficiency

capacity to predict words. It shows that all linear and quadratic components are significant, and the two-way interaction is inconsequential, making the model significant. The Fisher F test scored 63.24, suggesting that the model matches the experimental data.

Table 5 summarizes RSM predicted work compared with that of this present study with the type of pollutant used, method, number of runs, dependent variables, and independent variables.The initial RSM design technique—CCD, BBD, or FFD—received the greatest attention from researchers. Most reactors investigated four or fewer parameters, and the most common were methane output, biogas generation rate,and COD removal efficiency. To better understand their applications, such as the BBD method used in trials with various parameters, techniques other than CCD must be optimized and designed. RSM may model and optimize more than four effective factors to boost meaningfulness and comprehensiveness (Jasni *et al.,* 2020).

CONCLUSIONS

RSM uses predictor variables and dependent variables or responses. It is more practical than statistical significance tests for optimizing variables/ factors (point estimate is the statistical jargon). Two case studies showed that the ANFIS was faster and more accurate than standard optimization approaches such as the genetic algorithm. The ANFIS produced all fuzzy inference system-required fuzzy data. Fuzzy inference system reduces application development, execution, and maintenance expenses, among others. Fuzzy inference systems are more compact (require fewer rules); encode high-level information even in the designer's native language; are less error-prone; can handle ambiguous, uncertain, and imprecise input; are simpler to maintain. Finally, Sugeno FIS can model and create hybrid systems such as ANFIS and linguistic hedges. RO 16 was batch sorptioned on *P. juliflora root* hydrochar in this study, and RSM and ANFIS optimized process conditions.

At pH 2, 2 g/L hydrochar dosage, 35°C temperature, and 250 mg/L starting RO 16 concentration, removal effectiveness reached 86.1%. ANFIS predicted higher values than RSM, with batch correlation coefficients of 0.9999 and 0.9997, respectively. Four input variables were utilized to produce a single output, with low, medium, and high membership functions applied to each. With minor errors, a correlation coefficient of 0.9999 between the experimental and projected values reveals that the model best matches the experimental data.This study shows that mathematical techniques can accurately estimate dye removal efficiency from aqueous solutions.

AUTHOR CONTRIBUTIONS

K. Prasanna reviewed the literature and evaluated the results, whereas J. Oliver Paul Nayagam conducted the experiments, analysed and wrote the report.

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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

°C	Degree Celcius
AARE	Absolute average relative error
Adj MS	Adjusted mean squares
Adj SS	Adjusted sums of squares
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANOVA	Analysis of variance
$C_{20}H_{17}N_3Na_2O_{11}S_3$	Emprical formula for Reactive Orange 16
cc	cubic centimeters
CC	Cubic Capacity
Ce	concentration after adsorption
CI	confidence interval
Co	concentration before adsorption
DF	Degrees of freedom
e.g	Exempli gratia (for example)
f-value	ratio of two variances
g/L	gram/litre
g/mol	Gram per molecule
Hz	Hertz
i.e.	Id est (that is)
kg	Kilogram
km	Kilometer
m	Meter
M	Magnitude
m/s	Meter per second (velocity unit)
m^2	Meter square
MASW	Pearson correlation coefficient
mg/L	Milli gram per litre
MPSED	Marquardt's percent standard error deviation
N	number of experimental observations

nm	Nano metre
NN	Neural Network
P	Number of factors
p-value	probability value
PI	Profitability Index
Qcal,i	calculated or predicted values of the models
Qexp,i	xperimental values
RMSE	Root mean square error
RO 16	Reactive Orange 16
rpm	Revlotions per minute
RSM	Response Surface Methodology
SE	standard error
T test	statistical test that is used to compare the means of two groups
V	total volume of dye to be treated
xi, xj	Independent variables
Y	Response
β0	Intercept
βi	quadratic
βii	linear
βij	Interaction effects
ε	Error

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ORIGINAL RESEARCH PAPER

Relationship between chlorophyll-a, sea surface temperature and sea surface salinity

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study aimed to investigate the long-term relationship between chlorophyll-a, sea surface temperature, and sea surface salinity monthly from January 2015 to December 2021. It was carried out in the Northern Bay of Bengal, which experiences extreme monsoons, in the southwest monsoon and northeast monsoon from June to September and November to February, respectively. Monsoon is the main cause of changes in chlorophyll-a, sea surface temperature and sea surface salinity.

METHODS: The seasonal model was used to examine the relationship between these three parameters, which were obtained using the Copernicus Marine Environment Monitoring Service data. The seasonal model was used to observe periodic patterns and predict parameters based on their regularity. Meanwhile, Pearson's correlation analysis was conducted to determine the relationship between chlorophyll-a, sea surface temperature and sea surface salinity.

FINDINGS: This study found that the three parameters, namely chlorophyll-a, sea surface temperature, and sea surface salinity, follow the monsoon pattern, as shown in the seasonal model. The minimum value of chlorophyll-a occurred in February, March and April, while the maximum value of approximately 2 milligram per cubic meter occured at stations 1, 2, 3, 4, 5 and 7, but at 9 and 10, it increased to 12-14 mg/m3. This indicates that station positions are very sensitive to changes in chlorohophyll-a values. When the southwest monsoon occurred, it reached the maximum. Furthermore, the minimum sea surface temperature values occurred in January and at almost every station in the year. It was shown to be associated with the northeast monsoon, which causes winter. On the sea surface temperature graph, several peaks were observed in positive local extremes yearly at almost all stations. The maximum sea surface temperature occurred in May, June, and July, according to the shape of the graph, which peaked in the middle of the year. The sea surface salinity graph formed a peak and valley which occurred yearly in May or April, as well as September and October, respectively.

CONCLUSION: Chlorophyll-a had 1 trough and 1 peak, with the sea surface temperature graph possessing only 1 peak, while the sea surface salinity graph had 1 peak and 1 trough, respectively. These graph patterns implied that chlorophyll-a first achieved a minimum value before reaching the máximum. The sea surface temperature graph had a maximum value in the middle of the year, while the minimum occurred at the beginning or end. Moreover, the sea surface salinity graph first reached the maximum value and then declined to the minimum.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
38	5	4

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INTRODUCTION

The Bay of Bengal (BoB) is bordered by the Indian subcontinent, Southeast Asia, and the northern Indian Ocean, with a complex bathymetry, as shown in Fig. 1. Generally, the climate in the Northern BoB (NBoB) is dominated by monsoons. The Northeast (NE) monsoon occurs from November to February and the Southwest (SW) monsoon from June to September (Goswami *et al.*, 2016). Fig. 2 shows the wind pattern in February and August 2021, which sequentially emerges from the NE and SW. The magnitude of wind stress is two times greater in August than in February. The average wind speed in August and February is approximately 6.3 meter per second (m/s) and 7 m/s, respectively.

According to Miranda *et al.* (2021), water quality variability in the NBoB is greatly influenced by the following factors, SW and NE monsoons which change seasonally, waste disposal from rivers and various industries on the coast, as well as frequent tropical cyclone (TC) events. Since the global thermohaline circulation is driven by density, it is paramount to study the relationship between sea surface salinity (SSS), sea surface temperature (SST), and chlorophyll-a (Chl-a). This is formed by salinity and temperature, the basic physical properties of seawater and the main drivers of global climate dynamics. These properties also affect oceanic biogeochemical cycles and the atmospheric carbon flux (Woolf *et al.,* 2016). As an important variable in climate change, SSS and SST strongly influence the hydrological cycle. (Belward *et al.,* 2016) stated that anthropogenic climate change tends to respond to the hydrological cycle. Some tracer in ocean circulation is determined by SSS, thereby making it an important factor in climate change (Bosc *et al.*, 2009). An extremely close relationship exists in the tropical Pacific between SSS and SST, which is detected through hydrodynamic processes (Zheng and Zhang, 2015). For example, as an external driver, the following factors SSS, density, and oceanic stratification are affected by freshwater flux, which tends to affect SST (Zhang and Busalacchi, 2009). El Niño-Southern Oscillation (ENSO) variability is caused by the SSS and SST anomalies near the dateline, characterized by its evolution (Qi *et al.*, 2019). According to Sahoo and Bhaskaran (2015), the observations made in BoB during 1998, 2001, 2005, and 2013 proved that there is a positive relationship between SST and cyclones. High SST results were found in extreme cyclone intensity, and concerning salinity, there has been a negative relationship between the upper oceanic stratification and post-monsoon TC intensification for the past two decades. TC tends to strengthen when this variable is low (Fan *et al.*, 2020). The depiction of cyclones in BoB over a long period (1877 to 2016) was documented by Bandyopadhyay *et al.* (2021). A positive relationship exists between its intensity and Chl-a concentration (Latha *et al.*, 2015). The impact of the spatiotemporal evolution of SSS needs to be studied because it closely connects with climate variability (Eyring *et al.*, 2016). The concentration of Chl-a and its primary productivity are affected by light penetration caused by the formation of a gradient due to SSS and SST, which is closely related to the distribution of nutrients and suspended sediments (Torregroza-Espinosa, 2021). Björn *et al.* (2009) stated that light harvesting and the conversion of an absorbed photon into chemical energy are two important and irreplaceable roles of Chl-a in oxygenic photosynthesis. Li *et al.* (2018) observed the leaves of 823 plant species and discovered that Chl-a, chlorophyll-b (Chl-b), and chlorophyll-a per chlorophyll-b (Chl-a/b) have an average value of 4.18 milligram per gram (mg/g), 1.72 mg/g and 2.47 mg/g, respectively. The study was conducted in nine Chinese forest communities from cold to tropical zones. In this circumstance, it appears that the value of Chl-a is greater than Chl-b. Li *et al.* (2018) categorized plant functional groups based on different Chl. It was reported that trees have lower Chl values than shrubs and herbs. Coniferous and evergreen trees have lower Chl values than broadleaved and deciduous ones. Some other studies reported that Chl-a, Chl-b, and total chlorophyll (Chl a+b) increase with higher latitude. In 2015 and 2016, seasonal changes, such as the SW and NE monsoons in NBoB, greatly affected the interannual variations of SST, SSS, and Chl-a (Dutta and Paul, 2021). During the NE and SW monsoons, NBoB becomes cool and relatively warm, respectively. This is in accordance with the observations conducted by Sarangi and Devi (2017). The SW and NE monsoons also affect SST variability and Chl-a production (Vecchi and Harrison, 2002). Choudhury and Pal (2010) reported that during the SW monsoon, SSS decreases due to the large discharge of fresh water from the Ganges and Brahmaputra rivers flowing into NBoB. There is an increase in SSS on the coastal periphery, which

positively correlates with a rise in phytoplankton production during the NE monsoon. During the rainy season, there is also an increase in the NBoB turbidity. Chauhan *et al.* (2005) reported a reduction of light penetration in the water column, which negatively impacts Chl-a production in the region. Several studies utilized the Copernicus Marine Environment data portal Monitoring Service (CMEMS). For instance, including Ikhwan *et al.* (2022) researched to determine mixed layer depth (MLD) using CMEMS salinity data. Similarly, Pisano *et al.* (2020) studied long-term oceanic variability with SST data, while Moradi (2021) tested the accuracy of Chl-a concentrations using in situ data collected from 2008 to 2018. Excellent results were obtained by comparing the CMEMS model and the concentration of float Chl-a (Biogeochemical-Argo (BGC-Argo), measurements data). This was indicated by a correlation coefficient and root mean square error (RMSE) of 0.81 and 0.59, respectively (Lamouroux *et al.*, 2019). Exceptional results were also obtained by comparing three-dimensional (3D) temperature data (in Kelvin) with in situ observation data at a depth of 0 to 5 meter (m). This was reflected by the root mean square (RMS), which comprises in situ thematic centre (INS TAC), which had a value of 0.65, and for Indian Ocean data on comparison with in situ CORIOLIS, having a value of 0.44. The comparison of 3D salinity data (in practical salinity unit (psu)) with in situ observational data showed excellent results. The RMS value at a depth of 0 to 5 m for global and Indian Ocean data was 0.65 and 0.204, respectively (Lellouche *et al.*, 2019). This present study was conducted to examine the relationship between Chl-a, SST, and SSS parameters monthly from January 2015 to December 2021. A total of 10 stations were selected in NBoB, as shown in Fig. 1 and Table 1. This process was achieved using the following three steps, namely 1) The graphs of the three parameters, including Chl-a, SST, and SSS for all stations, were plotted, 2) These led to the derivation of the seasonal model at all stations, 3) The correlations between Chl-a and SST, Chl-a and SSS, as well as SST and SSS at all stations were also obtained. Based on the literature review, the monthly long-term relationship between Chl-a, SST, and SSS in NBoB using the seasonal model and the correlation method has never been carried out. The seasonal model was used to analyze the behavior of Chl-a, SST, and SSS and the possible prediction of these three parameters. This present study is extremely relevant because it relates to the fisheries sector. This is caused by the monsoon, which plays an important role in the Chl-a cycle alongside, its interaction with SST and SSS in NBoB. According to Dutta and Paul (2021), this also influences the variability of the fish assemblage. Monsoons also affect the availability of nutrients in the upper layer of NBoB and trigger phytoplankton's expansion (Vinayachandran *et al.*, 2005). The diversity and composition of reef fish depend highly on SST, coral richness, shelf width, and Chl-a (Floeter *et al.*, 2001). Daqamseh *et al.* (2019) conducted study in the Red Sea and reported a correlation between Chl-a, SST, and SSS. Higher SSS and warmer SST coupled with lower Chl produce an uncomfortable environment for fish to live in. This study aims to investigate the long-term relationship between chlorophyll-a, sea surface temperature, and sea surface salinity in the northern Bay of Bengal, situated in India, Bangladesh, and Myanmar, monthly from January 2015 to December 2021.

MATERIALS AND METHODS

This present study was conducted in NBoB, located at coordinates 18°N to 24.6°N and 85°E to 95°E, and it focused on 10 stations, as shown in Table 1. The visualization for the stations studied is clearly shown in Fig. 1. The data used were monthly reports on Chl-a, SST, and SSS (Lellouche *et al.*, 2018). It was obtained from the Copernicus Marine Environment data portal Monitoring Service (CMEMS) website (Le Traon *et al.*, 2019). Meanwhile, the other data used included wind per 6 hours obtained from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis 1 (Kalnay *et al.*, 1996).

Seasonal model

Seasonal models aim to identify seasonal patterns and predict parameters based on regularity (Ikhwan *et al.*, 2022). Chl-a, SST, and SSS data were analyzed using this framework based on non-linear regression as stated in Eq. 1 (Haridhi *et al.*, 2016):

$$y = \alpha + \beta \sin(2\pi t) + \gamma \cos(2\pi t) \quad (1)$$

where, α, β, γ and t are the constant vertical displacement, the amplitude of the sine wave, cosine wave, and time, respectively.

Table 1: Study station location

No	Station	Longitude (°E)	Latitude (°N)
1	1	87.25	20.5
2	2	89	20.75
3	3	87.25	21
4	4	88	21
5	5	89	21
6	6	90	21
7	7	88.5	21.5
8	8	89.75	21.5
9	9	91	21.5
10	10	91.75	22

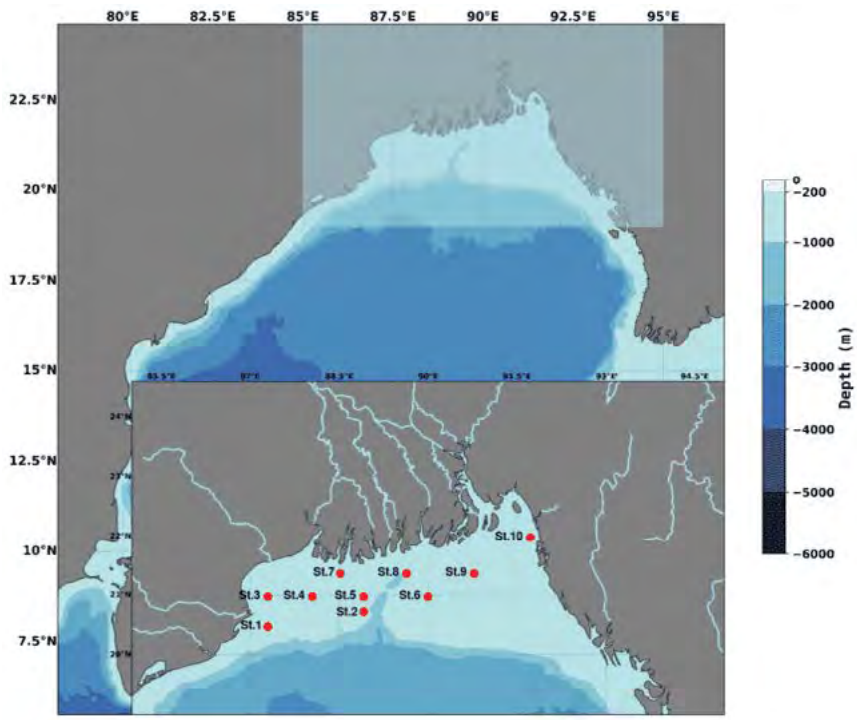

Fig. 1: Bathymetrical location of the study area in NBoB and the sample station (red dot). The map was plotted using Natural Earth raster + vector data (naturalearthdata.com). The blue color difference indicates the depth (m).

Correlation analysis

Pearson's correlation analysis was used to evaluate the relationship between Chl-a - SST, Chl-a - SSS, and SST - SSS. The correlation equation and coefficient used are stated in Eqs. 2 and 3 (Haditiar *et al.*, 2019).

$$y = b + ax, \tag{2}$$

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}. \tag{3}$$

Where $b, a, R,$ are the y-intercept constant, slope of the regression line (regression coefficient), and

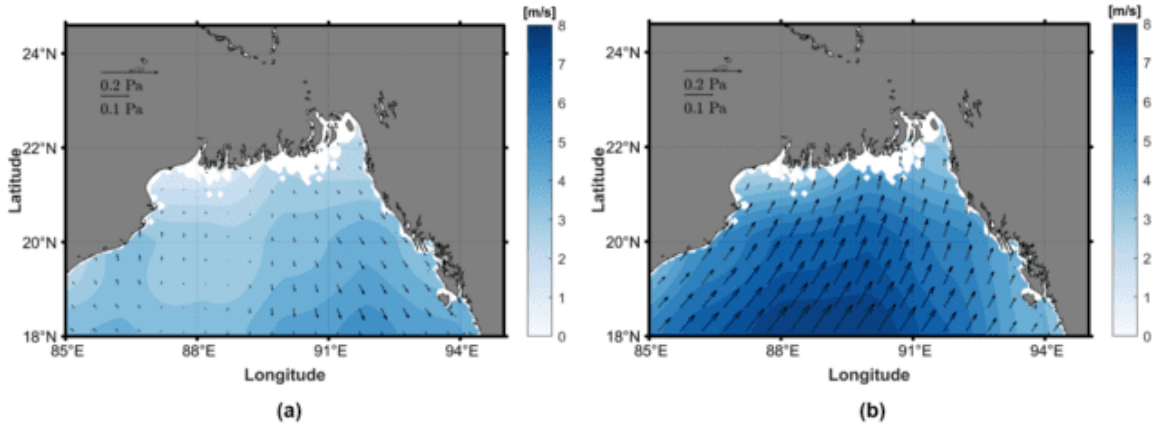

Fig. 2: The wind velocity (color in m/s) and wind stress (arrow in Pascals (Pa)) in (a) February and (b) August 2021, derived from NCEP/NCAR

correlation coefficient, respectively. The variables x_i and y_i are used to calculate the correlation coefficient between Chl-a and SST, Chl-a and SSS, as well as SST and SSS, where i is the corresponding data index, $\overline{x}$, and $\overline{y}$ is the average sample data of each station.

RESULTS AND DISCUSSION

Chlorophyll-a (Chl-a), sea surface temperature (SST), and sea surface salinity (SSS)

Fig. 3a, b, and c show the Chl-a, SST, and SSS, respectively, at stations 1 to 10 for seven years (2015 to 2021). Generally, the curve of Chl-a with respect to time is relatively flat and of low value from January to May, with peaks in different months. The minimum value realized in each year and station tends to differ. For example, in 2015, the minimum value was obtained in January, February, March and April. In 2016, the minimum value of Chl-a was detected in February, March and April. High concentrations of Chl-a occurred at stations 8, 9, and 10, namely between 6 to 14 milligram per cubic meter (mg/m^3). According to Dutta and Paul (2021), its peak reached a relatively 2 mg/m^3. Its domain in NBoB was within the range of 20°20′ to 21°30′ N and 87°30′ to 89° E. These tend to correspond to stations 1, 2, 3, 4, 5, and 7, which had an average Chl-a concentration of relatively 2 mg/m^3. Based on the results obtained, its peak at the earlier-mentioned stations occurred in July, August, and September. According to Dutta and Paul (2021), peak conditions generally occur between October and November. These differences might be because Dutta and Paul (2021) conducted a study on the NBoB in the domains 20°20′ to 21°30′ N and 87°30′ to 89° E in one station, while this present study was performed in 6 stations. Another interesting fact is that at stations 9 and 10, the concentration of Chl-a increased by relatively 12 to 14 mg/m^3, even though it was only 2°30′ E in the longitude direction from the other 8 stations and virtually no difference in the direction of latitude N. This implies that the values of Chl-a in NBoB are extremely sensitive to the positions of these stations, and this in turn has a significant impact on its concentration. Minimum values were detected in January, February, March, and April, while the maximum for all stations was observed in July, August, and September, during the SW monsoon period. Fig. 3b shows the SST values for each year at the 10 stations, in contrast to the relatively flat Chl-a at the beginning. The SST chart moved straight to the peak starting from the beginning of the year and then immediately decreased towards the end. Its minimum values, were detected in virtually every station and January. Occasionally, there was a shift in the minimum SST from January to December and February. This is associated with the NE monsoon, which causes winter. Dutta and Paul (2021) also noted that the minimum SST occurred every January from 2006 to 2015, with values ranging from 25 to 26 degree Celcius (°C). The minimum SST in this study was slightly lower, ranging from 23 – 25° C. Another characteristic of the SST graph is that there were several peaks in the form of positive local extremes every year at virtually all stations. The graph plotted by Dutta and Paul (2021) also showed similar characteristics, namely several positive local extreme

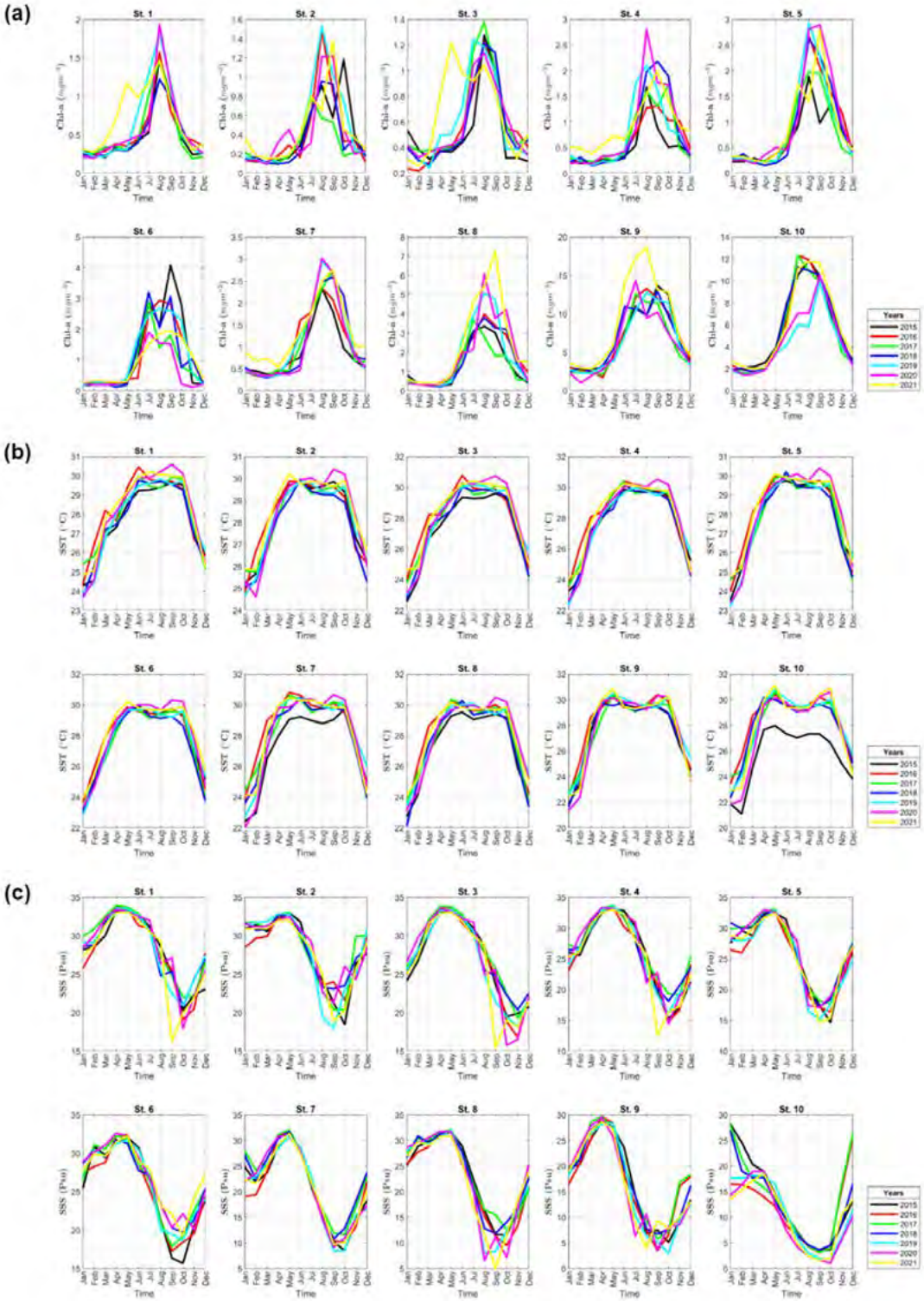

Fig. 3: Data of (a) Chl-a, (b) SST, and (c) SSS from Stations 1 to 10 for seven years (2015 to 2021)

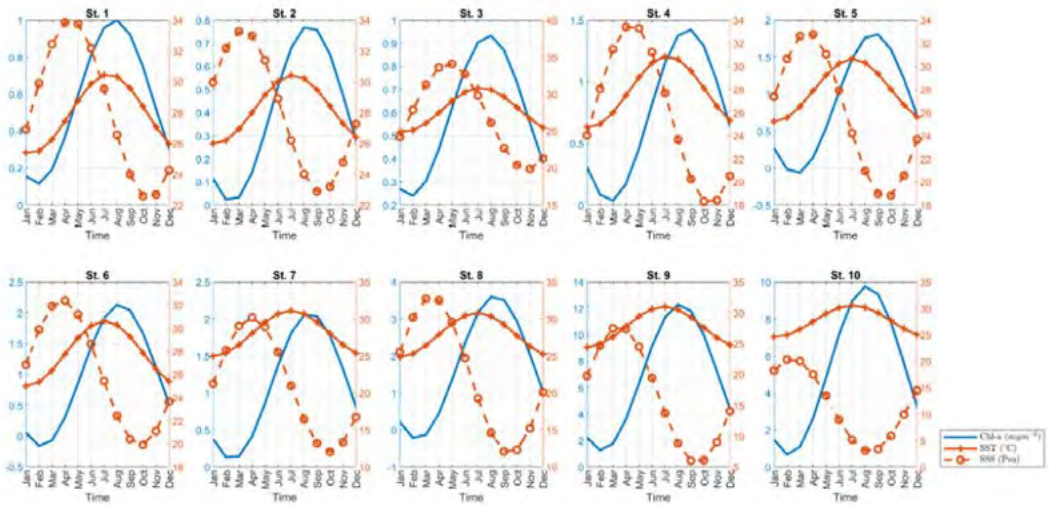

Fig. 4: Seasonal model of Chlorophyll-a (Chl-a) (solid line with blue color, in), Sea Surface Temperature (SST) (solid brown line with a plus symbol, in °C), and Sea Surface Salinity (SSS) (dashed brown line with empty bullets, in psu), with 10 sample station (St. 1-10). The position of the axis values of each graph corresponds to the color of the graph, namely the left ordinate for Chl-a (blue color) and the right ordinate for SST and SSS (brown color).

peaks. Based on Fig. 3b, the maximum SST occurred in May, June, and July, with its peak in the middle of the year. The SSS values from 2015 to 2021 at the 10 stations are shown in Fig. 3c. Its graph formed one peak and trough each year. The peak occurred in May or April, while the trough was observed in September and October. Dutta and Paul (2021) reported that the maximum and minimum values of SSS (34.76 psu) and (13.67 psu), were detected in May 2008 and September 2015, respectively.

Seasonal model

The data acquired from 2015 to 2021, were analyzed using the seasonal model, as shown in Fig. 4. This tool was used to simplify the analysis results at 10 stations, which produced repeated curve annually. The data tabulation in Table 2 summarizes the results obtained with this instrument.

The results of the seasonal model analysis in Eq. 1 are shown in Table 2, which summarizes the values of α, β, and γ for each of the Chl-a, SST, and SSS data. In general, Table 2 shows the behavior of the curves in Fig. 4. The constant α is a value that is not affected by the season, while β and γ are seasonally influenced constants. The average value of α in Table 2 indicates that the largest value for the variable Chl-a occurred at stations 9 and 10, while the least was detected at station 2. For the SST variable, the values of the largest and least constant α were found at stations 2 and 10, respectively. Finally, for the SSS variable, the largest and least values for constant α were found at stations 1 and 10, respectively.

Table 3 shows the peak and trough positions in Fig. 4 for each sample station in this study. The minimum (min) and maximum (max) values for Chl-a at 10 stations occurred in February and March, as well as August and September. The min and max SST values at 10 stations were observed in January and July, respectively. Meanwhile, the values in the SSS data for the 10 stations vary more than the other variables. The min value varied from August to November, while the Max was observed between February and May. Chaturvedi (2005) reported that stations 2 and 6 are consistent, thereby comparing them. The min and max SST was observed from January to February, and in November, respectively (Chaturvedi (2005). This is inconsistent with the results of this present study, where the Max SST occured only in July due to its inability caused by cloud cover from May to September (Chaturvedi, 2005). Furthermore, the Chl-a Max value in this study was obtained in August, while that of Chaturvedi (2005) was min and in November. The NE monsoon prohibited the Chl-a values due to salinity, while in SW the results were high.

Table 2: Constant and coefficient of predictor

No	Station	Chl-a			SST			SSS		
		α	β	γ	α	β	γ	α	β	γ
1	1	0.5577	-0.36477	-0.25254	27.92338	-1.67054	-1.94275	28.2245	4.2192	-3.9558
2	2	0.39621	-0.36212	-0.11621	28.21127	-1.27976	-1.80849	28.0884	5.185	-0.8231
3	3	0.58676	-0.28314	-0.20178	27.858	-1.7856	-2.406	27.002	4.3083	-5.7076
4	4	0.73014	-0.69313	-0.0868	27.8047	-1.7999	-2.4909	25.869	5.6126	-5.3555
5	5	0.873	-0.93425	-0.15681	27.94284	-1.41525	-2.30781	25.8049	6.8179	-2.1178
6	6	0.98587	-1.05471	-0.4609	27.8159	-1.4607	-2.4149	26.1491	5.7571	-2.4962
7	7	1.09303	-0.94727	-0.27758	28.0456	-1.5406	-2.6588	21.1214	7.9253	-4.4066
8	8	1.69226	-1.82073	-0.65607	27.8367	-1.4202	-2.6113	22.4157	10.3219	-2.3255
9	9	6.7795	-5.0123	-2.3524	27.7017	-1.5693	-2.8952	16.7618	10.7283	-2.7278
10	10	5.2156	-4.1246	-1.9426	27.5859	-1.5584	-2.5436	11.7085	8.3152	2.7693

Table 3: Peaks and troughs for the seasonal model

No	Station	Chl-a				SST				SSS			
		Min	Value	Max	Value	Min	Value	Max	Value	Min	Value	Max	Value
1	1	Feb	0.1155	Aug	0.9999	Jan	25.4056	Jul	30.4411	Oct	22.5927	Apr	33.8563
2	2	Feb	0.0245	Aug	0.7679	Jan	26.0052	Jul	30.4173	Sep	22.9034	Mar	33.2734
3	3	Feb	0.2407	Aug	0.9329	Jan	24.8815	Jul	30.8345	Nov	19.9049	May	34.0991
4	4	Mar	0.0370	Sep	1.4233	Jan	24.7476	Jul	30.8618	Oct	18.3306	Apr	33.4074
5	5	Mar	-0.0613	Sep	1.8073	Jan	25.2366	Jul	30.6491	Oct	18.8415	Apr	32.7683
6	6	Feb	-0.1580	Aug	2.1297	Jan	24.9942	Jul	30.6376	Oct	19.9152	Apr	32.3830
7	7	Feb	0.1339	Aug	2.0522	Jan	24.9727	Jul	31.1185	Oct	12.0546	Apr	30.1882
8	8	Feb	-0.2126	Aug	3.5971	Jan	24.8651	Jul	30.8083	Sep	12.0938	Mar	32.7376
9	9	Feb	1.2625	Aug	12.2965	Jan	24.4097	Jul	30.9937	Sep	6.0335	Mar	27.4901
10	10	Feb	0.6723	Aug	9.7589	Jan	24.6039	Jul	30.5679	Aug	3.1227	Feb	20.2943

Correlation analysis

The correlation images of the Chl-a – SST, Chl-a – SSS, and SST – SSS variable pairs for seven years are shown in Fig. 5. However, the tabulated data is shown in Table 4 to facilitate analysis. Fig. 5(a-j) shows the actual data curves of Chl-a, SST, and SSS, which are located in the first column position. The figures in the three consecutive columns explain the correlation between Chl-a – SST, Chl-a – SSS, and SST – SSS data. Based on the results obtained, Chl-a and SST data were shown to have a positive relationship. This is indicated by the slope of the regression line (blue line) that appears at the 10 stations investigated. A positive correlation signifies that the values of Chl-a and SST are directly proportional. This simply implies when the Chl-a value is high at a station, it will offset that of SST and vice versa. The actual data values in the first column, and the trend of the peaks and troughs on Chl-a (orange line), corresponding to the movement on SST. A negative correlation exists between the Chl-a and SSS data, except for the data acquired at station 3 as indicated by the slope of the regression line. The negative correlation suggests that the value comparison between Chl-a

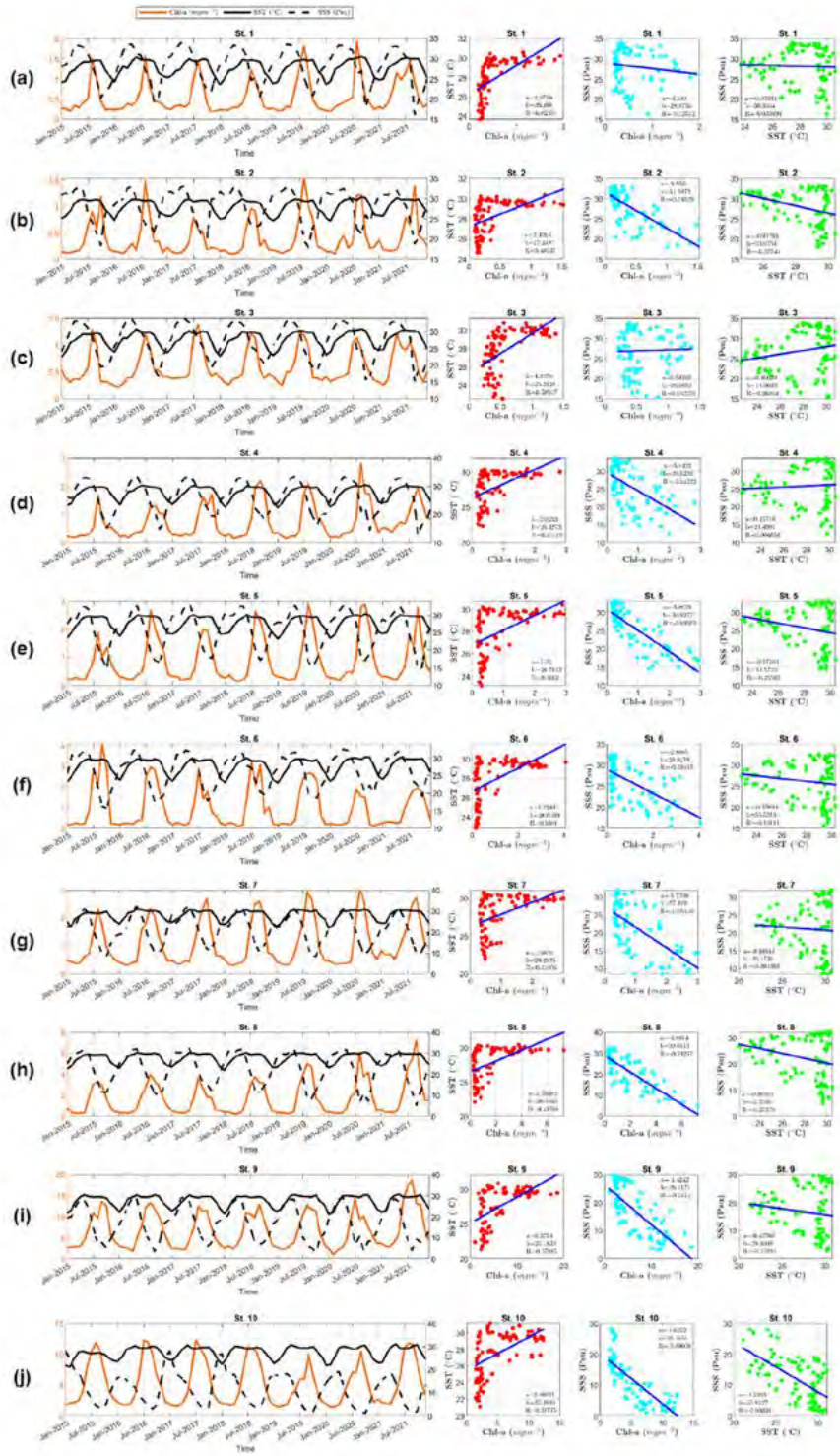

Fig. 5: (First column) Time series of Chl-a concentration (in solid brown line color), SST (in solid black line color), and SSS (in dashed black line) in the 10 stations (St. 1-10), which is marked by (a-j). Correlation analysis for Chl-a and SST (Second column), Chl-a and SSS (Third column), and SST and SSS (Fourth column) in the 10 stations (St. 1-10).

Table 4: Statistical data of all the variables

No	Station	Chl-a - SST			Chl-a - SSS			SST - SSS		
		a	b	R (corr coef)	a	b	R (corr coef)	a	b	R (corr coef)
1	1	2.97	26.27	0.62	-1.34	28.97	-0.13	-0.08	30.36	-0.03
2	2	2.43	27.25	0.50	-8.86	31.60	-0.75	-0.92	53.98	-0.38
3	3	4.34	25.31	0.59	0.54	26.69	0.03	0.47	14.01	0.20
4	4	2.02	26.33	0.52	-5.14	29.62	-0.54	0.16	21.50	0.06
5	5	1.35	26.76	0.51	-5.87	30.93	-0.84	-0.67	44.57	-0.26
6	6	1.22	26.62	0.54	-2.81	28.92	-0.59	-0.34	35.52	-0.16
7	7	1.61	26.29	0.51	-5.77	27.43	-0.66	-0.18	26.17	-0.06
8	8	0.79	26.49	0.54	-3.90	29.01	-0.79	-0.91	47.76	-0.27
9	9	0.37	25.18	0.58	-1.42	26.42	-0.74	-0.43	28.61	-0.14
10	10	0.40	25.49	0.53	-1.63	20.19	-0.81	-1.60	55.81	-0.60

and SSS is inversely proportional. When the Chl-a value is high at a station, that of the SSS tends to have an opposite trend and vice versa. The negative correlation between Chl-a and SSS corresponds to the real data curve in the first column. The Chl-a data curve (orange line) trend is the opposite of the SSS (dashed black line). In this case, the peak of the curve from the Chl-a data corresponds to the trough of the one from SSS. The trough of the curve from the Chl-a data corresponds to the peak of the one from SSS. For the cases encountered at station 3, the slope of the regression line was close to zero, meaning that the linear relationship between these variables is almost non-existent. The peaks and troughs of the Chl-a and SSS data curves do not correspond properly, thereby causing the correlation to be equivalent to zero.

The correlation between SST and SSS data was almost non-linear for stations 1, 4, and 7, while a positive relationship existed at 3. A negative relationship was detected in the remaining stations namely 2, 5, 6, 8, 9, and 10. The slope of the regression line, which was close to 0 at stations 1, 4, and 7, shows that the data varies and tends to spread out, therefore, there is virtually no linear relationship between the SST and SSS variables. The positive slope of the regression line at station 3 indicates that the comparison of SST and SSS values is directly proportional. For instance, when SST is high at this station, SSS will also be extreme, and vice versa. The negative correlation shown by the regression slope at stations 2, 5, 6, 8, 9, and 10 culminated in an inverse relationship between the SST and SSS variables. When the SST value increases, that of the SSS at these stations reduces and vice versa. The three types of relationships that occurred between these variables are described in the actual data curves in the first column of Fig. 5. At stations 1, 4, and 7, the SST and SSS curves were incoherent. In this case, the peaks and troughs of the curves shifted and were out of sync. The curve in station 3 indicates better synchronization as the curves' peaks and troughs appeared parallel, resulting in a positive correlation. A similar phenomenon occurred at stations 2, 5, 6, 8, 9, and 10. The peaks and troughs of SST and SSS appeared to be synchronous. The SST peak aligned with the SSS trough, while the SST trough vertically aligned with the SSS.

A summary of the statistical data from Fig. 5 is shown in Table 4. Schober (2018), stated that the correlation between Chl-a and SST pairs is moderate and positive at all stations, with a value of $0.50 \leq R \leq 0.62$. The relationship is strong and negative for the Chl-a and SSS pairs with a value of $-0.74 \leq R \leq -0.84$ at stations 2, 5, 8, 9, and 10. Meanwhile, at stations 4, 6, and 7, there was a moderate and negative correlation with a value in the range of $-0.54 \leq R \leq -0.66$. A weak and negative correlation occurred at station 1, with a value of R=-0.13, while station 3 were ignored, with a correlation value of R=0.03. For the SST and SSS pair, a moderate and negative correlation was obtained at station 10 with a value of R=-0.6. Weak and negative

correlations were observed at stations 2, 5, 6, 8, and 9 with a value of -0.14≤R≤-0.38. A weak and positive correlation was discovered at station 3, with a value of R=0.2. The correlation for stations 1, 4, and 7 were ignored because the R-value is close to zero.

CONCLUSION

The seasonal model and correlation analysis in NBoB were completed in this present study. The result is based on the fact that the three parameters, namely Chl-a, SST, and SSS, follow the monsoon pattern. Therefore, this relatively regular pattern is predictable. The occasional climate changes, such as El Nino and Indian Ocean dipole (IOD) events, which tends to cause a shift in wind direction, are a limitation. These events will, of course, affect the three parameters Chl-a, SST, and SSS. The correlation analysis also has certain limitations because it involves time series data. The CMEMS data used has a high resolution and reliability, as stated in the introduction. The Chl-a graph is relatively flat from January to May at the beginning of the year, then develops a peak in the subsequent months annually and at various stations. The Min values of Chl-a occurred in February, March, and April, while that of the Max was relatively 2 mg/m^3 at stations 1, 2, 3, 4, 5, and 7, but at stations 9 and 10, although it reached 12 to 14 mg/m^3. Besides, stations 9 and 10 were only 2° 30′ E in longitude from the other 8, meaning that their positions are extremely sensitive to changes in Chl-a values. When the SW monsoon occurs, Chl-a values reaches its Max, and this occurs in July, August, and September. The Min SST values were detected in January and in the year in virtually every station. Occasionally, there was a shift in the Min SST, from January to December. The Min SST is associated with the NE monsoon, which causes winter. The SST graph shows several peaks in the form of positive local extremes every year at virtually all stations. The Max SST occurred in May, June, and July, according to the shape of the graph. The SSS graph achieved it peak in either May or April, while the valley was observed in September and October. From the seasonal model, Chl-a and SSS graphs had 1 trough and 1 peak, respectively, while the SST graph had only 1 peak. This is because the Chl-a had a Min value at the initial chart pattern, before obtaining the Max. The SST graph had a Max value in the middle of the year, while the Min was realized at the beginning or towards the end. The SSS graph reaches the Max value and then declines to the Min. The results of the seasonal model produced a periodic curve where the peaks and troughs can be identified. The Min Chl-a value occurred in February and March, while the Max was obtained in August. The Min and Max SST values were detected in January and July, respectively. For the SSS variable, the Min values vary from August to November, depending on the station, while the Max occurred from February to May. The average correlation for Chl-a and SST parameters at 10 stations was R=0.544, indicating that the relationship is moderate and positive. The Chl-a and SST values for the 10 stations studied mutually support each other or are directly proportional. For Chl-a and SSS parameters, the average correlation was R=-0.582, and this shows that the relationship is moderate and negative. The values of Chl-a and SST are inversely related, for Instance when the Chl-a value is high, SST become low, and vice versa. The average correlation for the 10 stations studied shows a weak and negative relationship of R=-0.164 for SST and SSS parameters.

AUTHOR CONTRIBUTIONS

S. Rizal performed the literature review, experimental design, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. M.N. Hidayat performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. R. Wafdan performed the literature review, interpreted the data, prepared the manuscript text, and manuscript edition. M. Ramli performed the literature review, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. Z.A. Muchlisin performed the literature review, prepared the manuscript text, and manuscript edition.

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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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ABBREVIATIONS

3D	Three-dimensional
°C	Degree Celsius
°N	Degree North
°E	Degree East
a	The slope of the regression line (regression coefficient)
b	The y-intercept constant
BGC-Argo	Biogeochemical-Argo
BoB	Bay of Bengal
Chl	Chlorophyll
Chl-a	Chlorophyll-a
Chl-b	Chlorophyll-b
Chl-a/b	Chlorophyll-a per chlorophyll-b
Chl a+b	Total chlorophyll
CMEMS	Copernicus Marine Environment Monitoring Service
ENSO	El Niño-Southern Oscillation
INS TAC	In situ thematic centre
IOD	Indian ocean dipole
m	Meter
m/s	Meter per second
mg/g	Milligram per gram
mg/m³	Milligrams per cubic meter
max	Maximum
min	Minimum
MLD	Mixed layer depth
NBoB	Northern Bay of Bengal
NCAR	National center for atmospheric research reanalysis
NCEP	National centers for environmental prediction
NE	Northeast
Pa	Pascals
psu	Practical salinity unit
R	Correlation coefficient
RMS	Root mean square
RMSE	Root mean square error
SSS	Sea surface salinity
SST	Sea surface temperature
SW	Southwest
TC	Tropical cyclone

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ORIGINAL RESEARCH PAPER

Social learning activities to improve community engagement in waste management program

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ABSTRACT

BACKGROUND AND OBJECTIVES: Community engagement is crucial to overcome environmental issues, including waste management. Several education-based initiatives have been employed to improve community engagement in waste management programs, but the effects were not satisfied in changing resident behavior for sustainable engagement. Some studies suggested social learning as the solution to improve community engagement through practice-based and dialogue-based learning activities. Nevertheless, it needed more empirical evidence to show the effect. This study aimed to measure the effect of social learning on improving individual waste management behavior and how social learning influence it.

METHODS: Using SmartPLS 3.2.9, this study measured the causal relationship of social learning activities to individual affective and behavioral factors. This study involved 504 residents exposed to social learning activities in Kawasan Bebas Sampah/ Zero Waste Area program in Bandung City, Indonesia as the respondents to gather the data using survey method.

FINDINGS: The study found that social learning activities have significantly influenced waste management behavior indirectly through Affective factors. The data showed that Dialogue-based learning has no significant effect on Affective factors for all significance levels (β =-0.0862, P > 0.01). Instead, path model analysis indicated the mediating effect of Practice-based learning for Dialogue-based learning and Affective Factors, with the accuracy model at a moderate level (R2 = 42%; Q2 = 0.2258). Meanwhile, supporting facilities influenced both Practice-based learning (β = 0.3116, P < 0.001) and Affective factors (β = 0.4419, P < 0.001) significantly. Further path model analysis demonstrated that without "Affective Factors" being nurtured, learning activities and Facilities would not be able to improve behavior significantly, as all paths directing to Behavioral Domain (Intention and WMB) had an insignificant effect (P value > 0.05).

CONCLUSION: This study offered empirical evidence, showing the mechanism of social learning to improve waste management behavior. The Learning activities should combine Dialogue and Practice-based learning to influence waste management behavior significantly, while Affective factors become the direct effect of Learning Activities. Supporting facilities were required to support the learning by providing routine waste collection systems and recycling facilities beneficial for the residents. In order to improve the learning activity effectiveness, the facilitators need to pay more attention to the learning contents to nurture the expected Affective factors.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
87	7	8

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INTRODUCTION

Household or residential waste has dominated municipal waste composition in many developing countries (Banerjee and Sarkhel, 2020; Esmaeilizadeh *et al.,* 2020; Speier *et al.*, 2018; Jouhara *et al.*, 2017), including Indonesia (SIPSN, 2021). This dominance shows that residents are one of the core stakeholders for MSWM improvement (Aleluia and Ferrão, 2016; Kamaruddin *et al.*, 2017; Moh and Abd Manaf, 2017; Owamah *et al.*, 2017). Some literature also indicated that the residents play crucial roles in waste prevention, reduction, reuse, and recycling which become critical activities in MSWM (Al-dailami *et al.*, 2022; Soni *et al.*, 2022; Zorpas, 2020). Thus, residents are expected to engage the waste management sustainability actively. In environmental issues, community engagement allows heterogeneous people to act collectively for a more impactful program (Axon, 2016). Community engagement refers to not only reducing the risk of unsupported community to the waste management program (Goven *et al.*, 2012; Kallis *et al.*, 2021; McAfee *et al.*, 2021) but also changing community awareness, attitude, and behavior or lifestyle to support the waste management activities sustainably (Soni *et al.*, 2022; Axon, 2016, 2020). However, establishing proper engagement in waste management activities and sustaining their behavior is still difficult to reach (Axon, 2016; Azevedo *et al.*, 2021; Banerjee and Sarkhel, 2020; Gundupalli *et al.,* 2017). The terminology of engagement refers to not only knowing about the issue (cognitive) but also caring and being motivated internally (affective) and being able to take actions related to the issues (behavior) (Axon, 2016). It implies that the residents are internally motivated to join the waste management activity because their psychological factors agree, and they know how to do it and can do it. Osborne *et al.* (2021) also stated that community engagement means direct participation and involvement in social learning activities to improve understanding and interest in the addressed issues. This engagement will build trust as social capital among participants, change the community behavior, and willingness to collectively act for sustainable practice (Axon, 2016; Goven *et al.*, 2012; Osborne *et al.*, 2021). Several attempts were employed to improve community engagement in waste management activities through various interventions such as awareness campaigns or other educational-based strategies. However, some interventions only occurred temporarily (Gyimah *et al.*, 2019; Singer *et al.*, 2019; Yukalang *et al.*, 2018; Zamri *et al.*, 2020), causing temporary changing behavior only during the intervention (Bui *et al.*, 2020; Noguera-Méndez *et al.*, 2016; Zamri *et al.*, 2020). Some interventions were ineffective in changing the behavior due to their ineffectiveness in the process (Esmaeilizadeh *et al.*, 2020; Idamah, 2015; Moh and Abd Manaf, 2017; Setiawan *et al.*, 2019; Wang *et al.*, 2018). Meanwhile, other interventions relied only on a mass-based education approach, only facilitating one-way communication without any interaction, such as television (Almasi *et al.*, 2019; Idamah, 2015; Song *et al.*, 2016), articles/ newspapers (Chow *et al.*, 2017; Song *et al.*, 2016), social media/internet (Hammami *et al.*, 2017; Ma *et al.*, 2018). Such an approach only works for those who already have awareness and attitude toward waste management activities. According to previous studies, two-way communication and close interaction have become one of the core processes to build community engagement by changing their behavior sustainably (Axon, 2016; Osborne *et al.*, 2021; Vetter, 2020). Active action is also crucial for empowerment and ownership of the program (Osborne *et al.*, 2021). Enabling active action allows the community to perceive the values of the activities and improve their awareness and attitude toward the activities so that it builds new behavior, and develop new culture (Knickmeyer, 2020; Liao, 2018; Xu *et al.*, 2017; Yeh *et al.*, 2016).

Social learning for community engagement sustainability in waste management

To achieve sustainable community engagement in the waste management process, some literature suggested long-term intervention in the form of social learning to encourage sustainable improved behavior (Almasi *et al.*, 2019; Bui *et al.*, 2020; Idamah, 2015; Knickmeyer, 2020; Loan *et al.*, 2017; Navykarn and Muneenam, 2015; Noguera-Méndez *et al.*, 2016; So *et al.*, 2019; Sukholthaman and Shirahada, 2015; Zamri *et al.*, 2020). Social learning has been recommended as one approach to enable collective learning in various environmental-based programs for both developing and developed countries (Barrantes and Yagüe, 2015; Benítez *et al.*, 2020; Benson *et al.*, 2015; Goven *et al.*, 2012; Kristjanson *et*

al., 2014; Noguera-Méndez *et al.*, 2016). One of the approaches to implementing social learning in the community is using a framework called Community of Practice (CoP) (Kristjanson *et al.*, 2014; Madsen and Noe, 2012; Noguera-Méndez *et al.*, 2016; Tran *et al.*, 2018). The CoP concept was introduced by Wenger *et al.* (2002), who designed CoP as a source of learning for a particular community. The key to community engagement sustainability is the critical reflection on the relationship between knowledge (cognitive), affective, and action correlated with environmental problems (Abramowitz *et al.*, 2017; Axon, 2016; Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016). Social learning can facilitate it by enabling individuals, communities, and societies to learn through dialogue and practice and adapt their behavior to deal with change to achieve sustainability (Kristjanson *et al.*, 2014; Noguera-Méndez *et al.*, 2016; Tran *et al.*, 2018). In the social learning framework, learning and collective change become the core of engagement, addressing complex socio-ecological problems by joining various knowledge and value sharing at distinct levels (Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016). Through a dialogue and practice, social learning contributes to achieving more sustainable change in resident behavior toward waste management activities as it facilitates single-loop, double-loop, and even triple-loop learning (Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016). While single-loop learning is impactful in changing technical actions such as skills and procedures, double-loop learning modifies internal factors such as individual value, assumptions, belief, motivation, awareness, and intention through a mental model that defines the actions or behaviors (Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016). Triple loop learning goes beyond the individual, as it is the deepest level of learning as it modifies systems and nurtures social capital, such as changing social norms, law, and social culture (Keen and Mahanty, 2006; Noguera-Méndez *et al.*, 2016) for sustainable community engagement (Goven *et al.*, 2012; Osborne *et al.*, 2021). Social learning promotes effective learning as it is characterized as an iterative process of knowledge sharing through joint activities such as dialogue, collective action, and reflection. The activities encourage changes in practice, not only at an individual level but also in networks and systems, to reach a particular shared purpose (Keen and Mahanty, 2006; Kristjanson *et al.*, 2014; Noguera-Méndez *et al.*, 2016). Thus, social learning approach changes individual and community behavior toward waste management to reach sustainable waste management practice.

Research gaps and aim of the study

Social learning in the form of CoP has been implemented in a variety of domains in order to change community behavior, for instance, an agricultural-based community in Denmark (Madsen and Noe, 2012), South Australia (Raymond and Robinson, 2013) and Sweden (Nykvist, 2014). It was also implemented in learning groups of farming residents in Indonesia (Wulandhari *et al.*, 2021), Vietnam (Tran *et al.*, 2018) and dairy farmers in Europe (Dolinska and d'Aquino, 2016; Triste *et al.*, 2018). Some collective learning and action groups for the environmental initiatives are Canadian biosphere partnership communities across Canada (Reed *et al.*, 2014), Green Action Co-op in England (Bradbury and Middlemiss, 2015), and waste management learning activities in community-level Kawasan Bebas Sampah (KBS)/ Zero Waste Area (ZWA) in Bandung City, Indonesia (Ghazali *et al.*, 2021; Sunarti *et al.*, 2020). Even though social learning has been implemented in various domains and has shown its effects to change community behavior, it lacks of empirical evidence to show how it could affect community behaviors. Most previous studies focused on identifying the learning activities (both dialogue-based and practice-based learning) (Dolinska and D'Aquino, 2016; Jordan *et al.*, 2020; Noguera-Méndez *et al.*, 2016; Reed *et al.*, 2014; Tran *et al.*, 2018; Wulandhari *et al.*, 2021). Some other studies discussed only the learning outputs (Bradbury and Middlemiss, 2015; Dolinska and D'Aquino, 2016; Noguera-Méndez *et al.*, 2016; Nykvist, 2014; Vetter, 2020; Wulandhari *et al.*, 2021). Nevertheless, it was a lack of empirical evidence to measure how significant each social learning activity can affect the individual affective factors and behavior. Therefore, this study aims to measure the effect of social learning, characterized by dialogue and practice learning approach, on the individual behavior especially concerning waste management behavior domain. In order to facilitate the mapping of social learning activities, it was employed Socialization, Externalization, Combination, and Internalization (SECI Model) by Nonaka *et al.* (2008),

which are four postulates introduced by Nonaka *et al.* (2000) to explain the knowledge conversion among four different modes. According to Nonaka *et al.* (2008), there were primarily two types of learning to facilitate SECI: Practice-based learning and dialogue-based learning. Dialogue-based learning was powerful in facilitating externalization and combination as tacit knowledge can be expressed into formal language, and explicit knowledge can be deepened and refined (Nonaka *et al.*, 2008). Meanwhile, practice-based learning facilitates Socialization and Internalization as this activity allows sharing of tacit knowledge via shared experience and explicit knowledge embodiment into action as tacit knowledge (Nonaka *et al.*, 2008). This study was the follow-up of the current study by Ghazali *et al.* (2021), which proposed a model showing the relationship between two approaches of social learning (Dialogue and Practice) to Affective and behavioral factors through the qualitative method. This study was intended to give empirical evidence of the relationship among factors in the model and showed how social learning influenced waste management behavior. The study was located in *KBS* or Zero Waste Area, in Bandung City – West Java, Indonesia, based on Ghazali *et al.* (2021) study location. Bandung City is one of the cities in Indonesia that encourage community engagement in the municipal waste management system (Sunarti *et al.*, 2020), besides several other cities in East Java (Trihadiningrum *et al.*, 2017). This study was conducted in April-July 2021, located in eight sub-districts (*Kelurahan*) chosen as ZWA models in Bandung City, West Java, Indonesia.

MATERIALS AND METHODS

This study used a quantitative method, using a survey strategy to gather the data from eight locations of the ZWA Program located in Bandung City, West Java, Indonesia, as presented in Fig. 1.

This study focused on exploring the effect of social learning activities on residents' behavior toward waste management activities in the 8 locations of the ZWA program. Bandung City government was concerned with handling the waste problem by involving residents actively in the waste management system because the waste composition in Bandung City was dominated by food waste (as presented in Fig. 2) which was most likely from residential or households (Ghazali *et al.*, 2021). The resident involvement in the waste management system at the ZWA program was mainly in inorganic-organic waste separation (highly encouraged/mandatory) and organic waste recycling (encouraged). Waste collectors collected, and recycled the organic waste at recycling points around the ZWA areas. The residents can sell the inorganic waste at a Waste Bank or just give them freely to the waste collectors for their additional income. There were also simple recycling facilities provided, such as bio pores or many types of composters or biodigesters, at some locations in ZWA areas (Ghazali *et al.*, 2021) so residents could directly dispose of and recycle their waste if they were willing. In some areas without enough spaces for recycling points, the organic waste was transferred to city-level recycling points.

The total population of all studied areas reached 34.877 households, with a different number of each ZWA. The respondents were the person in the family who handled the household waste disposal in the study location. Therefore, the sample number was taken from each ZWA proportionally. Each sub-district had several hamlets (Rukun Warga/RW). Not all hamlets in every sub-district were actively involved in the program; therefore, the sample selection was taken only from the areas exposed to learning activities under ZWA program. The total number of residents in the areas exposed to the learning activities became the population. The total number of required samples was counted using Cochran's sample as Eq. 1 (Cochran, 1977).

$$x = \frac{Z^2 pq}{e^2} \tag{1}$$

The x in the above formula refers to the sample size. Assuming that the confidence level (Z) was 95% (resulting Z score of 1.96), the standard deviation (p) was 0.5, so that q became 1-0.5 = 0.5 (1-p), and the margin of error (e) 0.5, the number of samples required was 395. However, was provided 504 samples to make sure getting adequate data and anticipating data errors from the respondents during the data collection process. Detailed information about the sample is presented in Table 1.

The study sample was chosen through a combination of purposive and clustered random sampling, as presented in Fig. 3. Purposive sampling was conducted for specific situations in which the

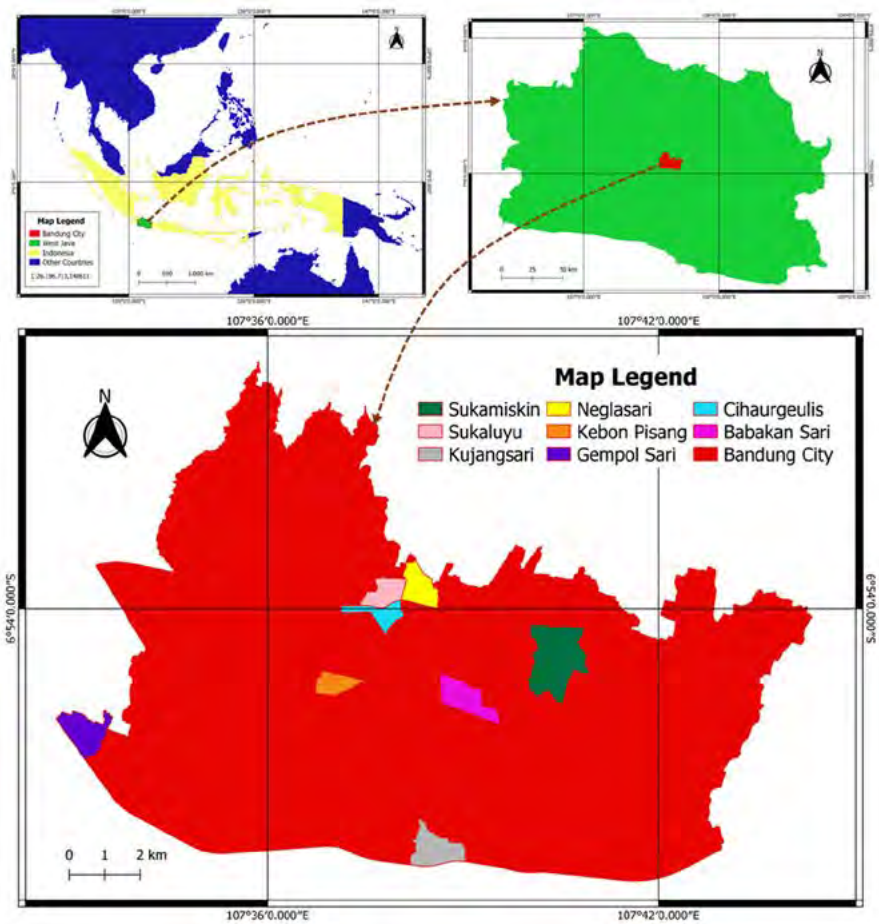

Fig. 1: Geographic location of the study arae plotted using an open source QGIS free software
(a) The study area Geographical location in Indonesia and its surrounding continents.
(b) West Java map were Bandung City is located (c) The study area with the eight study location points

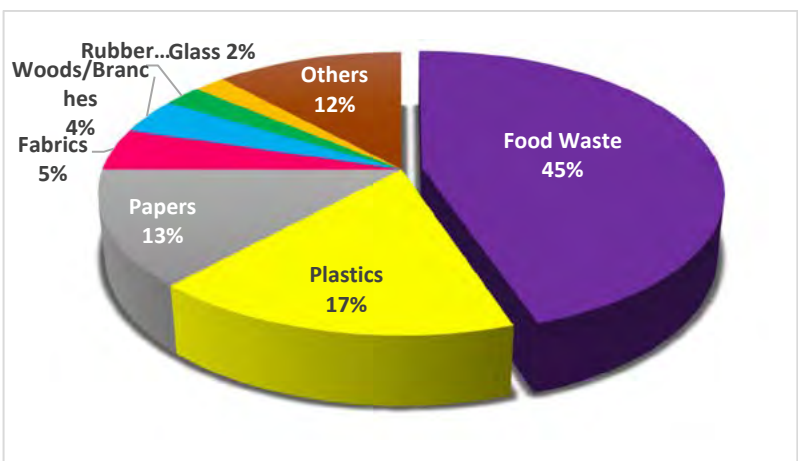

Fig. 2: Waste Composition in Bandung City, West Java, Indonesia (SIPSN, 2022)

Table 1: The Number of population in ZWA areas and samples for survey

No	ZWA areas	Number of households involved actively in waste management program	Sample prediction	Sample
1	Babakansari	± 500	50-70	70
2	Cihaur Geulis	± 800	80 - 100	103
3	Gempolsari	± 300	30 - 50	30
4	Kebon Pisang	± 400	40 - 60	60
5	Kujangsari	± 300	30 - 50	30
6	Neglasari	± 400	40 - 60	71
7	Sukaluyu	± 200	20 - 40	40
8	Sukamiskin	± 800	80 - 100	100
	Total number	± 37.000	370 - 530	504

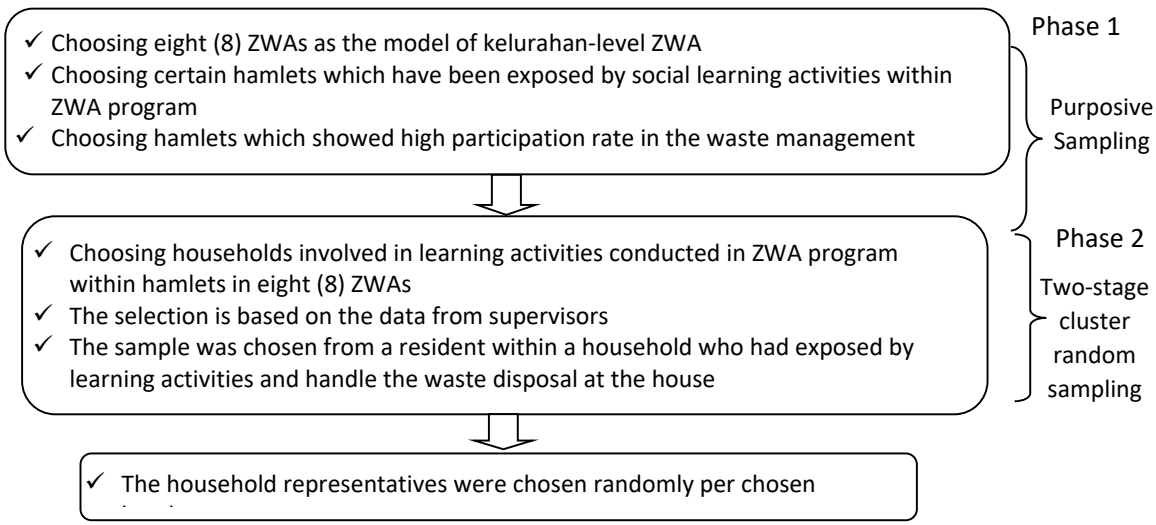

Fig. 3: Sampling technique for the respondents

sample selection was based on specific characteristics or requirements to enable the researchers to get broader information related to the purpose of the study (Neuman, 2014). The sample was first selected by choosing hamlet involved actively in learning activities, identified from the data of the supervisors. The households chosen as the respondents were randomly chosen to allow diverse resident profiles from each area.

Hypotheses building

According to qualitative data findings related to social learning activities in the ZWA program in Bandung City, Indonesia, two primary learning activities involved residents directly: Practice-based learning and Dialogue-based learning. The unit of analysis focused on residents, so some variables, such as key stakeholders' support and critical stakeholders' learning process, were excluded from the discussion. Both learning activities represented Socialization, Externalization, Combination, and Internalization. According to the informants, dialogue-based learning became the initial step of practice-based learning in which residents who had been given socialization through various approaches, such as Door-to-Door Education (DTDE), were asked to practice waste separation directly the next day. Therefore, some facilities were required, such as a waste collection system handled by the officers, separate waste bins, and recycling tools in the local areas. Therefore, the residents could separate their waste directly, recycle their waste if

Table 2. Hypotheses of the quantitative phase

	Hypothesis
H1	Dialogue-based learning activities significantly influence Practice-based learning activities
H2	Dialogue-based learning activities significantly influence affective factors
H3	Practice-based learning activities significantly influence affective factors
H4	Supporting Facilities system significantly influence Practice-based learning activities
H5	Supporting facilities system for significantly influence affective factors
H6	Affective factors significantly influence Intention to do waste management
H7	Intention to do waste management significantly influence WMB
H8	Dialogue-based learning activities significantly influence WMB
H9	Practice-based learning activities significantly influence WMB

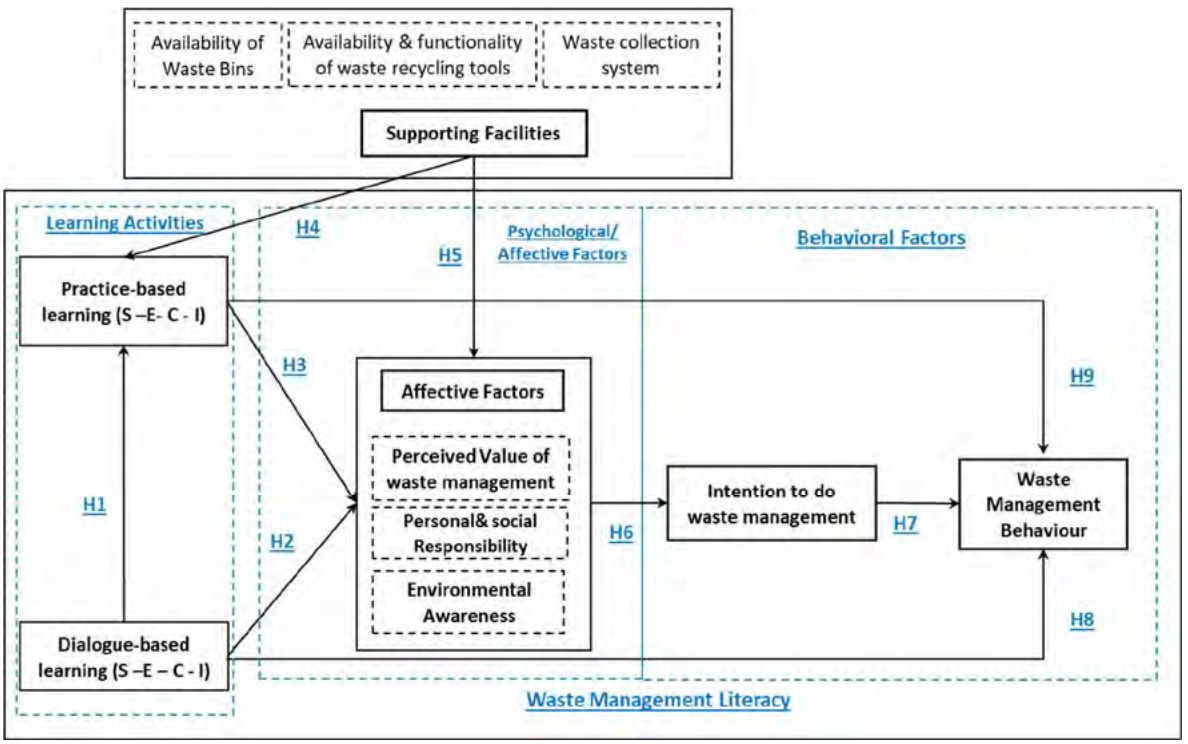

Fig. 4: Proposed model of the study

possible and feel the value of the activity. Learning activities in the ZWA program influenced Affective Factors resulting from individual self-reflection on double-loop learning. The Affective Factors identified and predicted to be impactful to waste management behavior (WMB) were Environmental awareness, Personal and Social responsibility, and Perceived value of waste management, precisely economic value, environmental value, social value, and religious value. The affective factors were predicted to nurture the behavioral factors represented through intention to participate and WMB. This study hypothesized that affective factors should mediate the relationship between learning activities and behavior. Therefore, to strengthen the hypotheses, the effect of learning activities on behavior was also measured for comparison. Therefore, several hypotheses describing the relationship among variables can be developed, as presented in Table 2. The proposed model that showed the overall relationship of all hypotheses measured in this study is presented in Fig. 4.

Questionnaire development

This study aims to measure the effect of social learning activities among households in the ZWA program by implementing the Partial Least Square Structural Equation Model (PLS-SEM) using SmartPLS 3.2.9. The measurement items in the questionnaire used in this study were established mainly from the findings in the qualitative phase on the study location (Ghazali *et al.*, 2021), combined with the literature review (Sunarti *et al.*, 2021). The literature review provided several significant variables affecting waste management behavior and predicted items to measure the variables. The qualitative findings determined which variables would be measured through the quantitative phase. The final questionnaire was refined based on the finding from the qualitative phase. Each indicator was measured by at least two indicators or measurement items. Each measurement item represented the construct weighting (Hair *et al.*, 2017). All indicators were ordinal, illustrated by the Likert scale with different points in some variables (3 points Likert point, 4 points Likert scale and 5-point Likert scale). The questionnaire was validated through two steps: expert validation and pilot test. The measurement items in the questionnaire before expert validation were 47 items. Three experts validated the questionnaire, resulting in three items being deleted because having similar meanings to other measurement items. Fifteen items were fixed without any revision, while twenty-nine items were revised in the sentences to make them more understandable and relevant to the measured variables. The pilot test involved 30 respondents, but the revision was only on the sentence structures especially in the clarity and ambiguity, without any item deletion. Once the data collection had been conducted, statistical reliability and validity tests were employed. Hair *et al.* (2017) recommended three common indicators to evaluate the reliability and validity of the model proposed: composite reliability, individual factor loading, and average variance extracted (AVE) to confirm the accuracy of latent variables measurement, the discriminant and convergent validities. The composite reliability (CR) value was associated with internal consistency among the involved latent variables, in which the threshold was 0.6 (Hair *et al.*, 2017), indicating that the internal model's consistency was robust. The threshold value for the individual loading factor was 0.5 to be significant. The AVE score was to show the discriminant and the convergent validities in which the higher the score, the greater the validities of the latent variables. The recommended value based on Fornell and Larcker was 0.5 and above (Hair *et al.*, 2017). The evaluation of the structural model (inner model), based on Hair *et al.* (2017), consisted of several steps because the primary goal of PLS-SEM was not only identifying significant path coefficients but also the relevance and significance of the effects. The overall evaluation process of structural model evaluation is presented in Fig. 5.

RESULTS AND DISCUSSION

Demographic characteristics of respondents

Detailed information about the demographic data of the respondents in this study is presented in Table 3. According to Table 4, respondents were 100% female because the chosen respondents were those who handled the waste disposal at home. The respondents were dominated by housewives (62,7%) while the age was spread, with the highest percentage: 40-49 years old (30,8%). The majority of the education level of the respondents was low because 81,2 % of the respondent's latest education was elementary-high schools. Meanwhile, the economic level was dominantly lower-middle class.

The profile of learning sources

Before residents filled out the questionnaire, the profile of learning sources was surveyed to ensure that the residents were involved in the learning activities in the ZWA program. The survey result was presented in Fig. 6.

According to the survey of learning sources from the respondents, it was found that the dominant learning sources were critical stakeholders in the ZWA program: DLHK educators (15.1%), KANG PISMAN cadres (14.6%), local cadres (PKK, Karang Taruna) (12.5%), local leaders (RT, RW) (12.3%), neighbourhoods 10.3%. This finding could prove that the ZWA learning program impacted the residents. It also indicated the crucial roles of educators from various resources, including the involvement of local people (including KANG PISMAN cadres, local leaders, waste collectors and neighbourhoods) to persuade the residents intensively. Employing local people in the community allows intensive interaction as they meet each other daily. This finding confirmed the

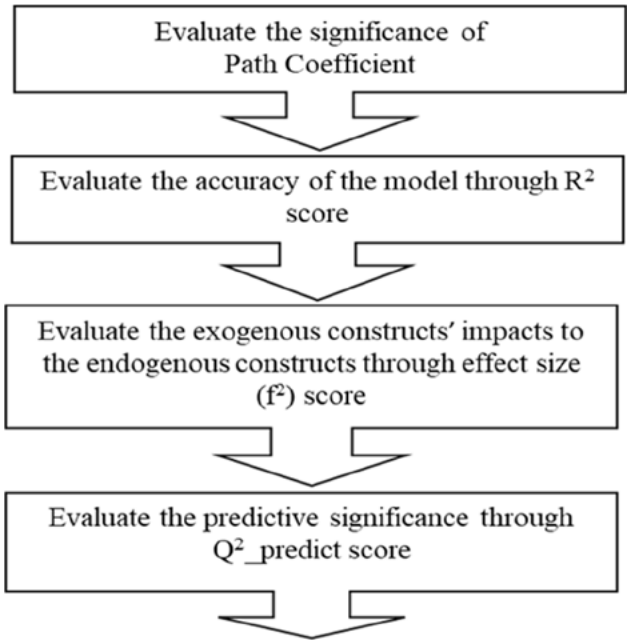

Fig. 5: The Procedure of structural model evaluation

Table 3: Demographic data of respondents

Variables	Frequency	%
Age		
20-29 Years Old	53	10.5
30-39 Years Old	111	22
40-49 Years Old	155	30.8
50-59 Years Old	132	26.2
> 60 Years Old	53	10.5
Occupation		
Housewives	316	62.7
Employees	188	37.3
Education Level		
Elementary-High Schools	409	81.2
Diploma	36	7.1
Bachelor	55	10.9
Postgraduate	4	0.8
Household Expense (/Month)		
Rp. 800,000,00-Rp. 1,810,000,00	293	58.1
Rp. 1,810,000,00-Rp. 4,572,000,00	185	36.7
More than Rp. 4,572,000,00	26	5.2

study by Pei (2019), who found that neighbourhood ties were crucial to support community learning about waste management in China. It could also be evidence that group learning (in a community) was essential to allow more interaction among neighbours. Knowles (1984) also pointed out social relationship to encourage adult learning. This data also showed that utilizing the internet and social media nowadays plays

Table 4. The reliability and convergent validity of improved model with deleted items

Constructs	Items	Outer loadings	Cronbach's α	CR	AVE
Dialog	DL1	0.5576			
	DL3	0.8140			
	DL4	0.7314	0.7281	0.8189	0.4814
	DL5	0.7753			
	DL6	0.5455			
Practice	PL1	0.6509			
	PL3	0.7253	0.6378	0.7847	0.4817
	PL4	0.5956			
	PL6	0.7441			
Supporting Facilities	WB1	0.3820			
	WB2	0.3276			
	WC1	0.7038			
	WC2	0.7390	0.6027	0.7395	0.3115
	WR1	0.3058			
	WR2	0.5133			
	WR4	0.7236			
Affective Factors	UR1	0.2812			
	UR2	0.6710			
	UR3	0.7653			
	UR4	0.3642			
	PV2	0.5546			
	PV3	0.6947	0.8446	0.8729	0.3777
	PV4	0.7034			
	PV5	0.4856			
	EA1	0.7006			
	EA2	0.5817			
	EA3	0.6039			
	EA4	0.7553			
Intention	I1	0.7341			
	I2	0.6985			
	I3	0.6410	0.7451	0.8306	0.4959
	I4	0.6899			
	I5	0.7524			
WMB	B1	0.6582			
	B2	0.6211			
	B3	0.6688	0.7185	0.8163	0.4718
	B4	0.7615			
	B5	0.7159			

a vital role in disseminating and socializing knowledge to a diverse society. However, these sources of learning only became additional to strengthen the effect of intensive learning, as indicated by Jiang *et al.* (2021). Furthermore, Sujata *et al.* (2019) pointed out that social media and websites could be utilized for knowledge storage while also becoming a learning source to reach residents outside the boundary area.

Data cleaning process

Before the data was analyzed using SmartPLS 3.2.9, data issue identification was conducted to delete some invalid and unreliable data. It could be done by measuring the Skewness and Kurtosis in SmartPL 3.2.9 or using BoxPLot in SPSS. In this study, it was employed the BoxPlot test using SPSS. The data from respondents were considered invalid when they showed extreme or unusual responses compared to the others or the question items. As a result, there were 33 data issues identified. After a manual screening, eight data issues were acceptable due to showing unique outliers to gave different insights for the findings, as Hair *et al.* (2017) implied that some outliers showing interesting cases may still be

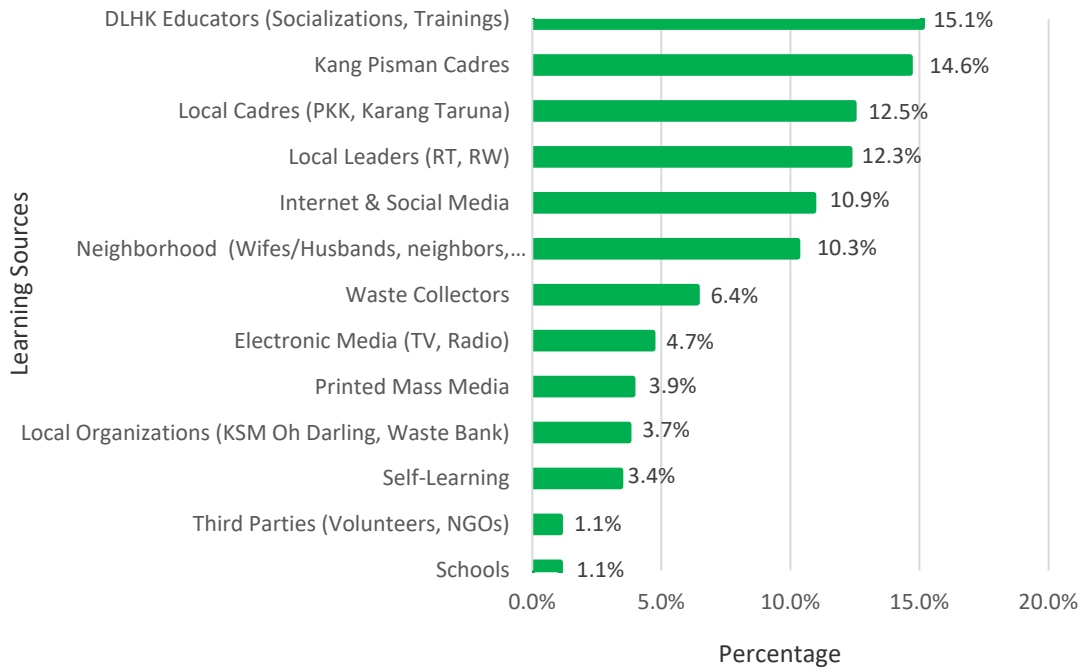

Fig. 6: Learning sources of residents in ZWA Program

Table 5: The discriminant validity of the revised model

Laten variable	Fornell-Larcker Criterion					
	Affective	Dialog	Facilities	Intention	Practice	WMB
Affective	0,6146					
Dialog	0,2196	0,6938				
Facilities	0,5922	0,2363	0,5582			
Intention	0,2795	0,2642	0,3225	0,7042		
Practice	0,5298	0,4901	0,5025	0,3124	0,6940	
WMB	0,3581	0,3679	0,3406	0,5802	0,3801	0,6868
Latent variable	**Heterotrait-monotrait ratio (HTMT)**					
	Affective	Dialog	Facilities	Intention	Practice	WMB
Affective						
Dialog	0,2735					
Facilities	0,7139	0,3657				
Intention	0,3415	0,3693	0,4707			
Practice	0,6655	0,6847	0,8071	0,4563		
WMB	0,4321	0,5192	0,5065	0,7830	0,5644	

required. Therefore, the eight data issues were still included in the analysis. The data issues excluded were those giving "Inconsistent Answer", "Straight lining", and "Outlier". Therefore, from the 504 total responses, with 25 exclusions, the final respondents became 477. Hence, the further analysis only involved 477 responses.

Outer model analysis

The outer model analysis consists of analysis toward reliability and validity of the measurement items such as Internal Consistency Reliability (Cronbach's Alpha), Composite Reliability (CR), Convergent Validity (AVE) and Discriminant Validity (Fornel Lacker Criteria and HTMT). As the questionnaire used in this study was based on qualitative findings, an exploratory analysis was conducted to eliminate invalid and unreliable measurement items to improve the validity and reliability of the overall measurement items. The first reliability and validity test output are presented in Tables 4 and 5.

Hair *et al.* (2017) suggested that increasing the validity and reliability of the measurement ítems could be done by deleting some less reliable and valid ítems (rules of thumbs for explorative study: 0.5) as long as the deletion could increase the overall reliability and validity score. According to Tables 5 and 6, some deletions of several items with outer loadings < 0.5 had increased the score for both Cronbach's α and CR. Similarly, deleting the higher-order constructs made the Discriminant Validity on Fornell-Larcker Criterion, and HTMT met the requirement. The subsequent problems were found on AVE. Due to the deleted items, the AVE score had improved, but the score was not reaching the standard yet. Thus, some more deletions of items were conducted. Some items with lower outer loading score were deleted to improve the AVE score. Thus, the final measurement ítems based on outer model evaluation were presented in Tables 6 and 7.

According to Table 6, some deletions of items with low outer loadings improved AVE and Cronbach's Alpha score. A similar situation was found for Discriminant Validity, in which the diagonal square of AVE was the highest.

Therefore, the final model evaluated in the next step only involved the items that passed the reliability and validity criteria. It is concluded that the valid and reliable items to describe Dialogue-based learning activities were from Externalization and Combination activities, for instance, involvement in informal discussion activity (Externalization) or training events conducted in the community. Meanwhile, items that described practice-based learning activities were Socialization and Internalization, in the form of learning directly to officers/cadres/neighbourhood about waste separation technique (Socialization) and learning by doing the waste separation every day. The direct practice enabled them to experience the effect of the routine activity (Internalization). These findings confirmed what Nonaka *et al.* (2008) explained: Socialization and Internalization occurred through direct experience, while Externalization and Combination occurred through dialogue and reflection. The reliable and valid predictors of supporting facilities were presented by waste collection system and recycling facility support, while waste bin distance and availability were could not predict it. Affective factors were significantly predicted by personal and social responsibility, environmental and social perceived value, and environmental awareness. The predictor of environmental awareness was significantly reflected by two occasions familiar to the respondents in ZWA areas, flood disasters and environmental pollution, as indicated by (Knickmeyer, 2020) and Lawrence *et al.* (2020). Regarding Intention and WMB variables, only organic waste recycling activities were invalid in predicting waste management intention and behavior. It is because, in the ZWA program, organic waste recycling activities became the responsibility of waste officers, while it was only voluntary for residents. However, recycling infrastructure was available in the neighbourhood, such as Bio pores, and composters, to facilitate the residents.

Structural model (Inner model)

The evaluation of the structural model is based on bootstrapping and blindfolding test procedures. The output for the evaluation model for both direct and indirect analysis was presented in Table 8, while the path model is presented in Fig. 7.

The effect of extrinsic factors on residents' affective factors

Two types of extrinsic factors were involved in the model: learning activities (dialogue-based and practice-based learning) and facilities. Each Extrinsic

Table 6: The final outer model

Constructs/latent variable	Item Code	Measurement items	Outer Loading	Cronbach's α	CR	AVE
Dialog	DL3	Do you often involve in discussion activities related to recycling waste?	0.8721			
	DL4	Do you often involve in training activities about making something from any kind of waste?	0.7982	0.8392	0.8818	0.5547
	DL5	I involve composting training so I can improve my composting skill	0.7606			
Practice	PL1	I learn how to compost/making handicraft from waste with the officer/cadre	0.6401			
	PL3	I understand how to separate waste correctly by practicing everyday	0.7826	0.7397	0.8523	0.6588
	PL6	Separating waste everyday makes me understand the benefits	0.8453			
Supporting facilities	WC1	Separated waste in my house was collected everyday by the officers	0.8128			
	WC2	Separated waste in my area was picked up routinely	0.8338	0.7464	0.8529	0.6592
	WR4	I hope the waste recycling facilities in my area give further benefits for us	0.7884			
Affective factors	UR2	I feel it is my responsibility to separate my waste at home	0.6979			
	UR3	Waste issue in our society can be solved if people and government have responsibility to overcome the problems	0.8009			
	PV3	I feel my house cleaner and more comfortable after I separate waste	0.7462	0.7088	0.8207	0.5344
	PV4	Separating waste will help the waste officer to do their job	0.7248			
	EA1	I am afraid that waste will pollute my environment	0.7191			
	EA4	I am afraid that flood will occur if I do not separate waste	0.7451			
Intention	I1	Are you willing to separate your organic waste (vegetables, fruits, etc)?	0.7636			
	I3	Are you willing to reduce your waste?	0.6640			
	I4	Are you willing to separate your inorganic waste (plastics, bottle, etc)?	0.7444	0.6267	0.8028	0.5789
	I5	Are you willing to take benefits of your inorganic waste?	0.7480			
WMB	B1	Are you used to separating your organic waste?	0.6921			
	B3	Are you used to reducing your waste with any kind of ways (ex: prefer reusable bag, bottle, etc to avoid disposable bags)	0.6607			
	B4	Are you used to separating your inorganic waste?	0.8266	0.6952	0.8141	0.5245
	B5	Are you used to utilizing inorganic waste for more valuable things? (example: making handicraft or other recycled products, etc)	0.7064			

factor path model was discussed in the following sub-chapter:

The effect of learning activities on affective and behavioral factors

Based on the structural model evaluation result presented in Table 8, it was shown that the Dialogue-based learning had no effect on Affective Factors directly, because the total effect is not significant (β = -0.0862, P value 0.070) which does not meet the threshold criteria (P <0,05). The effect level was also 0,0099, considered "no effect" according to Hair *et al.* (2017). However, Dialogue-based learning has médium significance to Practice-learning, with

Table 7: The final discriminant validity of the outer model

Latent variable	Fornell-Larcker criterion					
	Affective	Dialog	Facilities	Intention	Practice	WMB
Affective	0,7448					
Dialog	0,1688	0,8116				
Facilities	0,5708	0,1701	0,8119			
Intention	0,2755	0,1487	0,2717	0,7310		
Practice	0,5009	0,4830	0,3856	0,2688	0,7608	
WMB	0,3444	0,2618	0,2911	0,5736	0,3208	0,7242
Latent variable	Heterotrait-Monotrait ratio (HTMT)					
	Affective	Dialog	Facilities	Intention	Practice	WMB
Affective						
Dialog	0,2063					
Facilities	0,7013	0,2194				
Intention	0,3493	0,2057	0,3674			
Practice	0,6789	0,7086	0,5425	0,4020		
WMB	0,4395	0,3789	0,3934	0,8077	0,4785	

the P value reaching the minimum criteria for all significance levels. Meanwhile, the total indirect effect of Dialogue & Practice path analysis is significant, except the path that did not through Affective Factors (β = 0.0155, P Value 0.4610). It indicated that Dialogue-based learning should be mediated by Practice-based in order to be impactful to "Affective Factors", while the Affective Factors should be the learning activity result, instead of behavioral factors directly. In contrast, all path that showed the direct relationship between Dialogue and Affective Factors presented P Value below all threshold indicating no significant efffect found for the relationship. These path analyses strengthen the evidence that Dialogue should be mediated by "Practice", to significantly affected "Affective Factors". The mediating effect of "Practice-based learning" for "Dialogue-based learning" and "Affective Factors" was considered a moderate level, according to the f^2 effect value (see Table 8 for H1 and H3). Based on Fig. 7, the power of the model to explain "Practice-based learning" was up to 32,6%, weighed as "moderate" (Hair *et al.*, 2017). This finding has confirmed the crucial roles of combining Dialogue and Practice as a unit of learning approach facilitated by the CoP concept (Madsen and Noe, 2012; Nonaka *et al.*, 2008; Tran *et al.*, 2018). This finding also indicated the importance of habituation from practice-based learning as one of the most potent ways to achieve sustainable waste management behavior (Knickmeyer, 2020; Lawrence *et al.*, 2020; Liu *et al.*, 2018). The habituation activity implied that the dialogue and practice-based learning should be employed regularly in the long term because it takes time to change affective factors (Zebua and Sunarti, 2021; Yeh *et al.*, 2016). Considering the outer model finding as presented in Table 6, it pointed out that social learning need to start from a verbal communication approach (formally or informally), for instance dialogue or interaction in training activities, to allow the educators sharing fundamental knowledge and values with the residents (Sunarti *et al.*, 2021). Moreover, the interaction enables close relationship development between the residents and educators, which is vital for fluent knowledge sharing between individuals or among group of people (Wenger, 2002). The dialogue activities are combined by practice activities, such as guided direct practice with the educators/cadres/officers (Socialization) and personal practice day by day (Internalization). Eventually, the learning activities will improve

Table 8: Structural model evaluation

Hypothesis	Path model	Path coeficient (β)	P- value (T- value)			f^2 Effect size
			Total effect	Direct effect	Indirect effect	
H1	Dialogue → Practice	0.4305	0.0000 (9.7059) ***	0.0000 (9.7059) ***	-	0.2678
	Dialogue -> Practice -> Affective	0.1602	0.0000 (6.7927)	-	0.0000 (6.7927) ***	
	Dialogue -> Practice -> Affective -> Intention	0.0441	0.0000 (4.6246)	-	0.0000 (4.6246) ***	
	Dialogue -> Practice -> Affective -> WMB	0.0265	0.0006 (3.4543) ***	-	0.0006 (3.4543) ***	
	Dialogue -> Practice -> Affective -> Intention -> WMB	0.0219	0.0000 (4.4176) ***	-	0.0000 (4.4176) ***	
	Dialogue -> Practice -> WMB	0.0155	0.4610 (0.7378) ns	-	0.4610 (0.7378) ns	
H2	Dialogue → Affective	-0.0862	0.0700 (1.8158) ns	0.0351 (2.1131)**	-	0.0099
	Dialog -> Affective -> Intention	-0.0237	0.0529 (1.9400) ns	-	0.0529 (1.9400) ns	
	Dialog -> Affective -> WMB	-0.0143	0.0791 (1.7596) ns	-	0.0791 (1.7596) ns	
	Dialog -> Affective -> Intention -> WMB	-0.0118	0.0565 (1.9116) ns	-	0.0565 (1.9116) ns	0.1614
H3	Practice → Affective	0.3721	0.0000 (7.8042) ***	0.0000 (7.8042) ***	-	
	Practice -> Affective -> Intention	0.1024	0.0000 (4.7940) ***	-	0.0000 (4.7940) ***	
	Practice -> Affective -> WMB	0.0616	0.0005 (3.4941) ***	-	0.0005 (3.4941) ***	
	Practice -> Affective -> Intention -> WMB	0.0509	0.0000 (4.5173) ***	-	0.0000 (4.5173) ***	
H4	Facilities → Practice	0.3116	0.0000 (7.0327) ***	0.0000 (7.0327) ***	-	0.1403
	Facilities -> Practice -> Affective	0.1159	0.0000 (5.8869) ***	-	0.0000 (5.8869) ***	
	Facilities -> Practice -> Affective -> Intention	0.0319	0.0001 (4.0574) ***	-	0.0001 (4.0574) ***	
	Facilities -> Practice -> Affective -> WMB	0.0192	0.0012 (3.2486) ***	-	0.0012 (3.2486) ***	
	Facilities -> Practice -> Affective -> Intention -> WMB	0.0159	0.0001 (3.8825) ***	-	0.0001 (3.8825) ***	
	Facilities -> Practice -> WMB	0.0112	0.4778 (0.7104) ns	-	0.4778 (0.0112) ns	
H5	Facilities → Affective	0.4419	0.0000 (15.2637) ***	0.0000 (10.8264) ***	-	0.2884
	Facilities -> Affective -> Intention	0.1216	0.0000 (5.0871) ***	-	0.0000 (5.0871) ***	
	Facilities -> Affective -> WMB	0.0731	0.0003 (3.6800) *	-	0.0003 (3.6800) ***	
	Facilities -> Affective -> Intention -> WMB	0.0605	0.0000 (4.7728) ***	-	0.0000 (4.7728) ***	
H6	Affective → Intention	0.2751	0.0000 (6.2673) ***	0.0000 (6.2673) ***	-	0.0819
	Affective → WM Behavior	0.1655	0.0000 (6.4989) ***	0.0001 (4.0536) ***	-	0.0324
	Affective -> Intention -> WMB	0.1369	0.0000 (5.6685) ***	-	0.0000 (5.6685) ***	
H7	Intention → WMB	0.4975	0.0000 (14.3657) ***	0.0000 (14.3657) ***	-	0.3655
H8	Dialogue → WMB	0.1406	0.0000 (4.3524) ***	0.0015 (3.2008) ***	-	0.0246
H9	Practice → WMB	0.0361	0.0023 (3.07) ***	0.4596 (0.7400)ns	-	0.0012

ns = not significant; * p <0,10; ** p <0,05; *** p <0,01; (based on two-tailed significance)

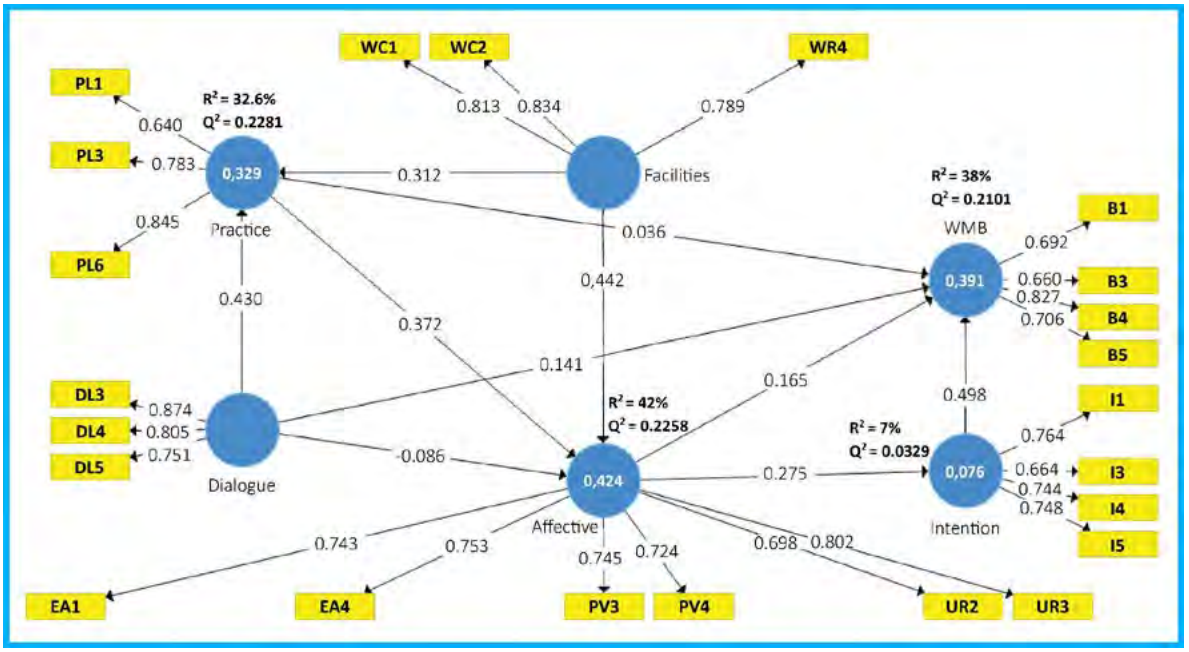

Fig. 7: Path coefficient significance of the proposed model

resident affective factors represented through personal and social responsibility, environmental and social perceived value, and environmental awareness (according to outer model test result). This finding also confirmed the qualitative finding from earlier study phase which revealed that most of the interviewed residents stated they could feel the benefits once they knew and practiced waste management directly (Ghazali *et al.*, 2021).

The effect of supporting facilities to practice-based learning and affective factors

The second extrinsic factor in the model was "Supporting Facilities", represented through routine waste collection systems, recycling facilities and the benefits of recycling products. A routine waste collection system refers to the availability of somebody-in-charge to collect separated waste routinely within the área. Meanwhile recycling facilities refer to the availability of tools to enable residents and or officers to recycle the separated waste directly in the area. It was hypothesized that "Supporting facilities" affect both "Practice-based learning" and "Affective Factors" directly. The path analysis result presented in Table 8, was proven that "Supporting facilities" directly affected both constructs significantly with P value for both 0.0000 (significant for all significance level). This finding supported the previous studies, which found a positive and significant relationship between facilities and affective factors (Wichai-utcha and Chavalparit, 2019; X. Liu *et al.*, 2019). However, the path analysis in Fig. 7 demonstrated that the effect of supporting facilities to affective factors is more significant than the effect of practice-based learning activities which typically nurture affective factors. This finding is in contrast to previous studies such as Kattoua *et al.* (2019), who contended that facilities' availability could not guarantee residents to participate in waste management activities unless they had enough environmental awareness and technical knowledge about it, which was resulted from learning activity (Ghazali *et al.*, 2021). There were two possible explanations for this phenomenon. First, it could be because the practice-based learning activities conducted in the ZWA program were not effective enough to nurture affective factors causing less impact on affective factors compared to supporting facilities. This argument is supported from the qualitative study in the previous phase (Ghazali *et al.*, 2021) which revealed that most of the educational contents in both learning approaches in the ZWA program focused heavily on technical knowledge,

such as waste separation and waste recycling, while other crucial waste issues were neglected. Whilst educational content is vital in determining what affective factors are being nurtured (Sunarti *et al.*, 2021; Janmaimool and Denpaiboon, 2016; Song *et al.*, 2016). Second, the supporting facilities variable could be more impactful to nurturing Affective Factors rather than learning activities because one of the indicators was about the expectance of residents toward recycling facilities' benefits. This indicator could represent their understanding of recycling activities, so they had expectation related to it. A previous study also showed that the expectation of benefits from recycling facilities was powerful in nurturing the residents' affective factors, especially perception of the activities' value (Wang *et al.*, 2020). Regardless of the different impacts given to Affective Factors, the path model test for both learning activities and Supporting facilities significantly shaped Affective Factors, indicating the vital role of the facilitator, either from the government or local leader, in initiating and facilitating the system.

The effect of affective factors resident affective factors on behavioral domains (Intention and waste management behavior /WMB)

According to the outer model analysis, the affective factors were well presented by three sub-variables: Personal and Social Responsibility, Perceived Value and Environmental Awareness. Personal responsibility points out the personal conscience or belief of responsibility about the waste issues due to their action, whereas social responsibility is someone's belief in society's role in waste issues (Table 6). The perceived value refers to the environmental and social value represented through perceived benefits once they have conducted the waste management activities. The benefits include a comfortable environment due to the cleanliness (environmental perceived value) or satisfaction feeling when they could help the waste collectors (socially perceived value). The last representation of Affective factors as the direct effect of social learning is environmental awareness, described by the feeling of whether their unfriendly behavior will cause harmful effects to their environment, such as environmental disaster (flood) or environmental pollution (Sunarti *et al.*, 2021; Zhang *et al.*, 2019). So, when the residents know the impacts of waste they dispose of (from dialogue-based learning), they know they have responsibility for waste management and are aware of the harmful impact if they do not manage their waste correctly. Table 8 indicated that "Affective Factors" were crucial to mediate Extrinsic factors (social learning and facilities) and behavioral factors (Intention and WMB). The path model analysis demonstrated that without "Affective Factors" being nurtured, learning activities and Facilities would not be able to improve behavior significantly, as all paths directly to Behavioral Domain (Intention and WMB) had an insignificant effect with accuracy model at moderate level (R^2 42%; Q^2 0.2258). Moreover, the path coefficient of learning activities (Dialogue-based and Practice-based) to WMB directly showed a low score (weak effect), indicating the vital function of Affective Factors to be nurtured as a mediator. This finding confirmed prior studies' findings which have proven that Learning Activities could not directly improve behavioral factors (Intention and WMB) unless Affective Factors mediated the relationship (Chen and Gao, 2020; Lissah *et al.*, 2021; X. Liu *et al.*, 2019; Pierini *et al.*, 2021; Sunarti *et al.*, 2021; Wang *et al.*, 2018). Based on the R^2 measurement effect, the model had moderate power to explain "Affective Factors", as much as 42%, implying that the model had 42% capability to predict the accuracy of Affective Factors. This capability was considered moderate, indicating that the Affective factors accurately predicted the path model. In terms of "Intention", Table 8 shows that Affective Factors had a significant effect on both "Intention" and WMB" directly. However, the P value of the indirect effects was higher than the P value to WMB. It means, the "Affective Factor" should improve "Intention" before affecting the WMB. However, according to the R^2 for Intention, the model had weak power to explain "Intention", which was only 7%. It indicated that the model had only 7% capability to predict the accuracy of Intention. This weak power could happen due to the absence of other Affective factors that played roles in this relationship. It confirmed what suggested by Sunarti *et al.* (2021), in which there were several layers of Affective Factors which were nurtured sequentially to influence "Intention". Thus, further research may explore more deeply about Affective factors and establish a causal relationship among the Affective Factors for a more authentic relationship to the Behavioral domain. Aside from the weak power

of the model for "Intention, the mediating effect of Intention between the Affective Factor and WMB had a significant effect, similar to the finding from past studies (Loan *et al.*, 2017; Meng *et al.*, 2019; Wang *et al.*, 2020; Xu *et al.*, 2017).

CONCLUSION

Resident engagement in the MSWM system is vital to ensure its effectiveness because residentials are considered the most dominant waste generators in MSWM. It requires an integrated, long-term, and structured system to allow residents to learn about waste management for sustainable engagement in the waste management system. This study has revealed that social learning is implementable to improve resident engagement in the waste management system in cities from developing countries, like Bandung City. This study has revealed some insightful findings using a model analysis measuring the effect of social learning activities at the ZWA program in Bandung City, West Java, Indonesia. First, to be impactful, social learning activities in the program should implement both a dialogue-based and practice-based approach, in which dialogue-based learning precedes the practice. Dialogue-based learning activities are employed through discussion and training involving residents individually and collectively to allow interactive communication for knowledge transfer and build close relationships among residents and educators. Meanwhile, practice-based learning is employed through the direct practice of waste separation or recycling activities, either guided by the educators or doing it themselves. This activity aims to habituating them with new habits while also allowing residents to sense the waste management activity's benefits directly. Second, the study findings implied that supporting facilities are crucial to bolstering practice-based learning activities (through the waste collection system and recycling facilities) and nurturing affective factors (personal and social responsibility, perceived value and environmental awareness). Third, the direct effect of social learning activities is an improvement in residents' affective factor, which mediate behavioral factors (intention and behavior). The improvement in affective and behavioral factors becomes the crucial component of community engagement for sustainable participation in waste management. The study findings can guide the government in developing countries or environmental-based communities to start a community-based waste management system in a particular area, especially in the area that has supportive culture to enable social learning. It is recommended to pay more attention to the contents that highlight the harmful impacts of waste on the environment, individual and social roles in waste issues and also the benefits of doing waste management activities. The knowledge-sharing activities should also be accompanied by direct practice for habituation daily. It is also suggested to choose relevant problems as an example of waste issues to allow residents to be more connected to the problems. This study was only focused on investigating social learning effects on an individual level, so the further study may also focus on measuring the third loop learning effect (social capital) at the community level.

AUTHOR CONTRIBUTIONS

S. Sunarti conducted the literature review and design the research, collected and interpret the data, and prepared the manuscript writing. R.S.Y. Zebua collected data, processed and analyzed the data using SmartPLS, interpret the data and prepared the map using QGIS. J.H. Tjakraatmadja validated the questionnaire related to SECI Model, analyzed and interpreted the data, review the manuscript. A. Ghazali. validated the questionnaire related to SECI Model, interpreted the data, and review the manuscript. B. Rahardyan validated the questionnaire related to waste management behavioral variables, interpreted the data, and review the manuscript. Koeswinarno collected and interpret the data, and prepared the manuscript writing. Suradi collected and interpret the data, review the manuscript. Nurhayu collected and interpret the data, review the manuscript. R.H.A. Ansyah Interpreted the data, review the manuscript and managed the references.

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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
3R	Reduce, reuse, recycle
AVE	Average variance extracted
B1,B3,B4,B5	Measurement items for waste management behavior
BRIN	Badan Riset dan Inovasi Nasional
CAQDAS	Computer assisted qualitative data software
CoP	Community of practice
CR	Composite reliability
DL3,DL4,DL5	Measurement ítems for dialogue-based learning
DLHK	*Dinas lingkungan hidup dan kebersihan*
DTDE	Door to door education
e	Margin of error
EA1, EA4	Measurement ítems for environmental awareness
f2	Effect Size
GPS	*Gerakan pungut sampah*
HTMT	Heterotrait-monotrait ratio
I1,I3,I4,I5	Measurement item for Intention
K3	Kebersihan, ketertiban, keindahan
KANG PISMAN	Kurangi pisahkan manfaatkan
KBS	Kawasan bebas sampah
KM	Knowledge management
KSM	Kelompok swadaya masyarakat
MSWM	Municipal solid waste management
MSW	Municipal solid waste
NGO	Non-government organization
ns	Not significant
PKK	Pembinaan Kesejahteraan Keluarga
PL1,PL3,PL6	Measurement items for practice-based learning
PLS - SEM	Partial least square structural equation model
PV3, PV4	Measuremen items for perceived value
p	Standard seviation
p value	Probability value
q	1- p
Q2	Predictive significance
QGIS	Quantum geographic information system

R2	Model accuracy
RT	Rukun tetangga/hamlet
RW	Rukun warga/ community association
SECI	Socialization, externalization, combination, internalization
SIPSN	Sistem informasi pengelolaan sampah nasional
SPSS	Statistical package for the social sciences
t Value	Size of the difference
UR2,UR3	Measurement items for responsibility
WMB	Waste management behavior
WC1, WC2	Measurement items for waste collection
WR4	Measurement item for waste recycling
x	Sample size
Z	Confidence level
ZWA	Zero Waste Area

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ORIGINAL RESEARCH PAPER

Toxicity of nickel oxide nanoparticle in *Capoeta fusca, using* bioaccumulation, depuration, and histopathological changes

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ABSTRACT

BACKGROUND AND OBJECTIVES: The nanoparticles has been discussed in terms of their adverse global impacts on health and health inequity. Metal oxide nanoparticles and their salts can have varied toxic effects on different tissues in the aquatic environments. The aim of present study was to assess the toxicity of nickel oxide nanoparticles in relation to different nickel salts.

METHODS: Acute toxicity of nickel oxide nanoparticles, nickel sulfate, nickel nitrate and nickel chloride, in black fish was investigated. A total of 125 fish were randomly assigned to a control group (n=25) and four exposure groups (n=25 per group). After 28 days of exposure, the bioaccumulation of nickel oxide nanoparticles in gill, intestine, liver, and kidney of the fish was determined by killing half of them in each group and dissecting their tissues. The remaining fish were placed in clean water for another 28 days and the depuration rate was estimated.

FINDINGS: The $LC_{50\text{-}96}$ values reported for nickel oxide nanoparticles, nickel sulfate, nickel nitrate and nickel chloride were 195, 120, 138 and 91 milligrams per liter, respectively. Therefore, nickel chloride had a higher toxicity compared to nickel oxide nanoparticles, nickel sulfate and nickel nitrate. The highest rate of nickel oxide nanoparticles bioaccumulation was observed in the gill (0.40±0.08 microgram per gram), intestine (41.82±16.95 microgram per gram), liver (2.16±1.82 microgram per gram), and kidney (2.16±1.26 microgram per gram) of the fish. The highest depuration rate of nickel oxide nanoparticles, nickel sulfate, nickel nitrate, and nickel chloride was recorded in the intestinal tissue of the fish. The lowest depuration rate of nickel oxide nanoparticles, nickel sulfate and nickel nitrate was observed in the kidney tissue of the fish. Also, the lowest depuration rate of nickel chloride was witnessed in the gill tissue of the fish. Histopathological anomalies were detected in the fish exposed to nickel oxide nanoparticles. These anomalies were fusion of lamellae, lamellar synechiae, curvature and oedema in the gill; increased number of goblet cells and cell swelling; and degradation of villi structure and expansion of villi structure in the intestine.

CONCLUSION: The study conclusively demonstrated that nickel oxide nanoparticles were ecotoxic and harmful to aquatic organisms. Strong global nickel oxide nanoparticles regulations must be enforced to prevent further environmental contamination with nanoparticles.

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44	5	5

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INTRODUCTION

Every year, millions of tons of nanoparticles are produced and released by powerful global industries into the environment (Giese *et al.,* 2018), while there is little to no regulations restricting the nanoparticles (NPs) environmental release. However, recently, in a welcomed turn of events, European Commission has banned a common nanoparticle, which is used as food additive, and a few nanoparticles frequently used in cosmetics. In general the multi-billion-dollar nanotechnology industry, runs wild with no regulations to restrict its risky activities. Measured in billionths of a meter, nanoparticles are comparable in size to viruses, proteins, and antibodies that can freely pass cell membrane and impact the molecules inside each cell, leading to serious allergic reactions in humans (Borgsteede *et al.,* 2021). Additionally, carcinogens, mutagens, and reproductive toxicants (collectively referred to as CMRs) have the potential to cause asthma (The UK Health, and Safety Executive). Additive toxicity can stem from NP reactions with other pollutants (Iftikhar *et al.,* 2021; Kamyab *et al.,* 2022). NPs have the potential to increase environmental toxicity because of their uncertain shape, size, and chemical composition (Dunphy Guzmán *et al.,* 2006). NPs have even been discussed in terms of their adverse impacts on global health and health inequity (Salamanca-Buentello and Daar, 2021). Riverine, freshwater, and marine ecosystems are the final depository for many NPs (Balaraman *et al.,* 2022). They are ommonly found in solid waste, wastewater effluent, direct industrial discharges, and accidental spills. Nickel oxide nanoparticles (NiO NPs) are of interest in this study because they are carcinogens with low solubility and high stability in water. They can easily be ingested by aquatic organisms (Gong *et al.,* 2016). NiO NPs also have high production rate and are widely used in multiple industries including solar and fuel cell manufacturing, automobile catalytic converters, lithium-ion batteries, and biosensor devices (Salama *et al.,* 2020). Gill, intestine, liver, and kidney, which readily absorb and accumulate contaminants, are appropriate tissues for histopathological examination. NiO NPs damage to fish internal tissue can be accurately assessed by histopathological examinations (Bais and Lokhande, 2012; Alijani Ardeshir *et al.,* 2017). Current state of knowledge suggests that metal oxide nanoparticles and their salts can have varied toxic effects on different tissues in the aquatic environments. For instance, Se-NPs are more toxic than Se salts in gill and liver tissues of iridescent shark catfish (*Pangasianodon hypophthalmus*) (Kumar *et al.,* 2018), and silver nanoparticles are more toxic than silver salts to gill and liver of European carp (*Cyprinus carpio*) (Liaqat *et al.,* 2021). However, iron nitrate [Fe $(NO_3)_3$] salt is more toxic than iron NPs in different tissues of black fish (Sayadi *et al.,* 2020). Based on the available information, no study yet have been carried out on the comprehensive ecotoxicological evaluation of the effects of NiO NPs in relation to their salts in black fish. The present study strives to compare the toxicity of NiO NPs and different nickel salts in black fish. In fact, the aim of this study was to compare the acute toxicity, chronic toxicity, and histopathological alterations of NiO NPs to different nickel salts in the fish. The uptake and depuration kinetics of different nickel compounds in the varied tissues of the fish were also investigated. This study has been carried out in University of Birjand, Birjand city, Iran in 2021.

MATERIALS AND METHODS

NiO NPs and nickel salts characterization

NiO NPs with 99.5 percent (%) purity was obtained from Twig Leaf Lane, Houston, TX, USA. Nickel salts (nickel sulfate, [$NiSO_4$], nickel nitrate [Ni $(NO_3)_2$], and nickel chloride [$NiCl_2$]) were procured from Merck, Germany. Energy Dispersive Spectroscopy (EDS) was used to determine the presence of NiO NPs; scanning electron microscopy (SEM) was applied to illustrate the morphology of NiO NPs; and X-ray Diffraction (XRD) and X-ray Photoelectron Spectra (XPS) were utilized to investigate the properties of NiO NPs. X-ray signals are arranged from lower to higher energy according to their atomic number. Elements in each sample were semi-quantitatively identified. Each peak was assigned to a specific atom. Higher peaks signify higher concentrations of an element in the sample. XRD was used to examine the properties of crystals. XPS is a surface-sensitive method which analyzes the chemicals on sample surface. This method was used to assess the purity and chemical composition of NiO NPs.

Black fish (Capoeta fusca) and test conditions

Black fish, native to eastern Iran, were collected from Eshkaftook aqueduct (59°09.6878'N 32°97.9754'W) in April and June 2021. Fiberglass aquarium containing 200-liter water from the aqueduct, with an aeration system, was used to transfer the fish to Birjand

University Limnology Laboratory. To keep the water clean and free of bacteria and other pathogens, 50% of aquarium water was replaced with clean water until the start of the experiment (10 days). During this period, the average water temperature was kept constant and the fish were fed twice a day (1% body weight).

Acute toxicity

Acute toxicity tests were carried out under controlled laboratory conditions, and used to determine the lethal dose/concentration of a substance that causes death in 50% of the test population (lethal dose 50 or LD_{50}/LC_{50}) during a short-term exposure. In other words, LC_{50} was used as a way to measure the short-term poisoning of the substance. It is the amount of a toxicant that causes death to half of a group of test animals when given at once. NiO NPs, and other nickel salts were obtained from Merck Company (Germany) in a powder form. Using distilled water, a 1000 milligram per liter (mg/L) dilution was prepared and placed on an ultrasonic device for 30 minutes until a homogeneous and uniform solution in composition was obtained. Then, serial dilutions of NiO NPs and nickel salts were prepared to assess their acute toxicity and LC_{50}. 1, 10, 20, 30, 50, 100, 200, 300 and 400 mg/L dilutions were prepared. LC_{50} was determined for each compound. For LC_{50} determination, the fish (n=10) were exposed to nickel compounds for 24, 48, 72 and 96 hours. After dosing the fish, the dead fish were quickly removed from the aquarium and the number of the dead fish at each concentration were recorded. Mortalities at 24, 48, 72 and 96 hours were used to calculate Lethal Concentration 50 (LC_{50}). For LC_{50} calculations, average body length and average body weight were recorded (LC_{50}; OECD 1993).

Chronic toxicity studies

Chronic toxicity tests typify adverse effects following repeated administration of a test substance over a significant portion of test specie's life span. The lower sub-lethal concentration (LSC) is commonly used for chronic toxicity testing. It dosed the fish with one tenth (1/10) of LC_{50} for chronic toxicity testing as follows: NiO NPs (19.49), $NiSO_4$ (12.02), Ni $(NO_3)_2$ (13.80), and $NiCl_2$ (9.12) mg/L. Fig. 1 describes the study design for determining bioaccumulation and depuration (chronic toxicity) of NiO NPs and nickel salts. Briefly, a total of 125 fish were randomly assigned to a control group (n=25), and four exposure groups (n=25 per group). After 7, 14 and 28 days of exposure to NiO NPs and nickel salts, 3 fish were removed from each aquarium and their gill, intestine, liver, and kidney tissues were removed for analysis. The remaining fish (n=15 per group) were placed in clean water. After another 7, 14, and 28 days in clean water, 3 fish were killed, and their tissues were similarly dissected for analysis.

Acid digestion of tissues

Gill, intestine, liver, and kidney of each fish were removed and separately placed in glass tubes. 5 millilitre (mL) of nitric acid (HNO_3, 65%, Merck, Germany) and 2.5 mL of perchloric acid ($HClO_4$, 70%, Merck, Germany) were added to each tube. Glass tubes were then placed in a water bath (TW12, Julabo Co., Germany) at 100 °C for 4-6 hours. Fully digested samples were passed through a filter paper (Whatman grade 40, Nikoshimi Co, Iran). Then the paper was discarded and the remaining liquid (~ 5 mL) was washed with distilled water into another plastic tube. The volume of each tube was filled with distilled water up to 20 mL. Concentration of nickel ions in individual tissues of each fish was measured using the graphite furnace atomic absorption spectroscopy (ContrAA 700, Analytik Jena AG, Germany).

Histopathological examinations

For histopathological examination, two fish from each aquarium were removed at 28 days. Their gills and intestines were removed and fixed for 24 hours in a 10% formalin buffer. The fixed tissues were dehydrated for an hour in 90%, 95% and 100% alcohol solutions. A 30-minute treatment of the samples with xylene, rendered them transparent. The samples were then molded using liquid paraffin (60°C). The tissues were cut in 5 µm thick slices using a microtome. Afterwards, the tissue slices were placed on glass slides and kept in the oven (37 °C). Hematoxylin-eosin was used to stain slides, and a light microscope (Nikon, eclips-E200) was applied to obtain photographs from each slide. Histopathological changes of the tissue were classified into four groups: nil or no changes (-), mild (+), moderate (++) and severe (+++) (Jerome *et al.,* 2017). Tissue alterations, compared to the control, were recorded using an Axio Vision Real 4.8 software. Finally, the qualitative data were collected.

Toxicokinetic modeling

A one-compartment first-order model was used to describe Ni uptake and depuration in the fish.

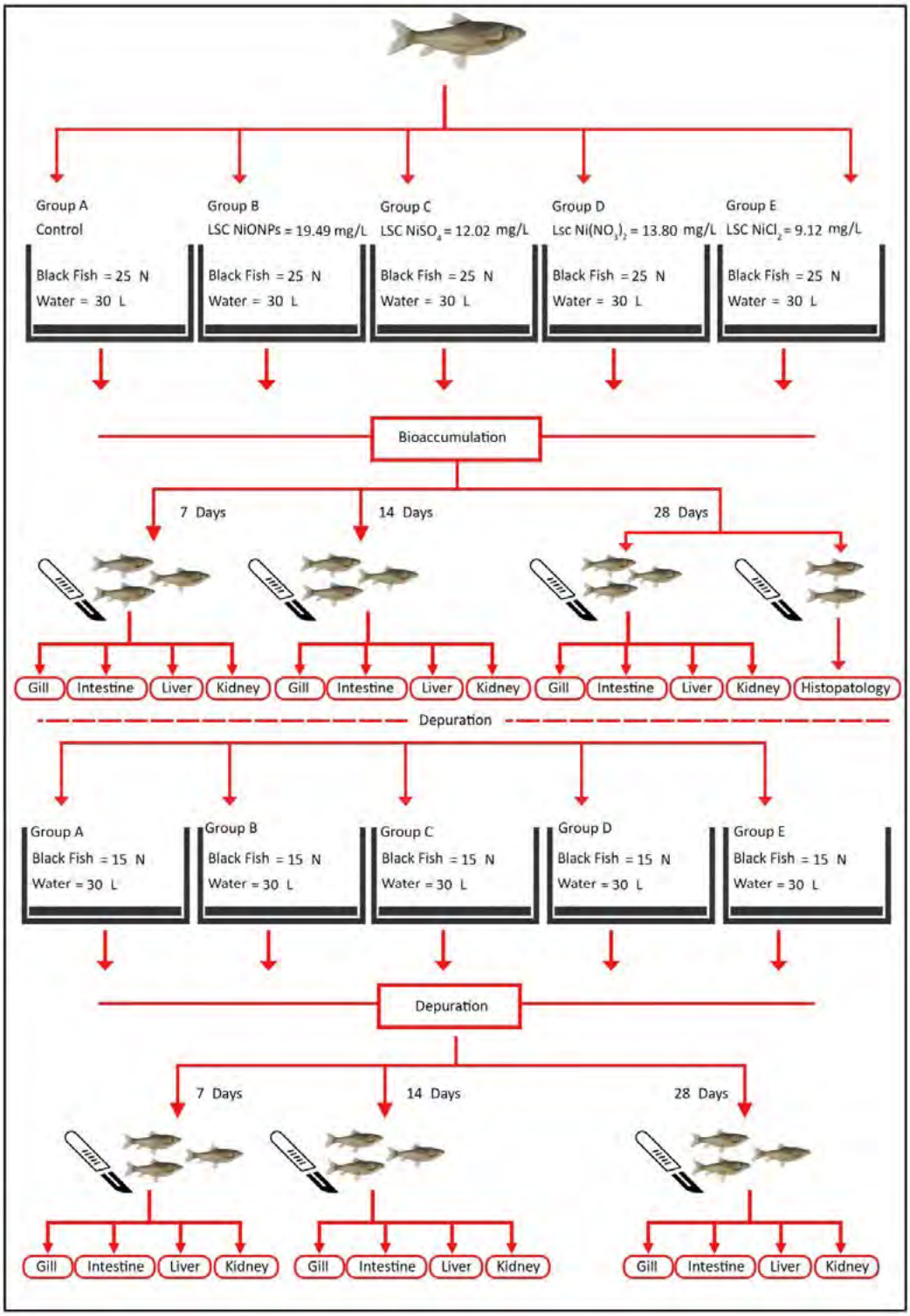

Fig. 1: Study design, including the number of fish in each group and the lower sub-lethal concentrations (or LSC) of toxicants used for determination of bioaccumulation and depuration (chronic toxicity) of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ and $NiCl_2$ in black fish (*Capoeta fusca*)

Background concentration in the fish was assumed to be constant. C_0 is the amount of toxicant in fish at time zero (Sun *et al.,* 2018). Model 1 (uptake), and model 2 (depuration) are described according to Eqs. 1 and 2, respectively.

Model (1) uptake:

$$Q(t) = C_0 + K_1/K_2 * C_e * (1 - e^{(-k_2 * t)}) \quad (1)$$

Model (2) depuration:

$$Q(t) = C_0 + K_1/K_2 * C_e * (e^{(-k_2 * (t - t_c))} - e^{(-k_2 * t)}) \quad (2)$$

Where, Q(t) is Ni concentration in fish in microgram per gram (µg/g) at the time of sampling t; C_0 is the concertation in an organism in terms of µg/g dry body weight at time zero; K_1 is uptake rate constant (per day); K_2 is depuration rate constant (per day); C_e is the exposure concentration in an environment in terms of µg per liter (µg/L); t_c is a period when an organism is transferred to a fresh uncontaminated water (on an hourly basis); and t is the sampling time in hours. These constants allowed for bio-concentration factor (BCF) to be evaluated, because it was assumed that Q(t) has reached a stable state. The BCF and the time when the organisms needed to undergo elimination of half-life of nickel ($T_{1/2}$) were calculated using Eqs. 3 and 4 (OECD 2016).

$$BCF = K_1/K_2 \quad (3)$$

$$T_{1/2} = Ln(2)/K_2 \quad (4)$$

Statistical analysis

SPSS software version 20 was used for all the data analyses. Significance was put at p= 0.05, and One-way ANOVA with Tukey-Kramer post hoc test was used to evaluate the effects of NiO NPs and nickel salts exposure on the fish. LC_{50} values were calculated using Probit analysis with Microsoft Excel.

RESULTS AND DISCUSSION

Ecological studies often use fish response to toxicants and assess damage caused by pollutants like Ni. Changes in molecular physiology and behavior of fish, as a result of exposure to Ni, have been reported (Sibiya *et al.,* 2022). In the present study, NiO NPs and nickel salts were put under comprehensive ecotoxicological evaluation for the first time. This study aimed to increase the current knowledge of Ni and its NPs. It described acute and chronic toxicity of NiO NPs, their histopathological effects, and their uptake and depuration kinetics. These parameters were compared to elucidate the effects of nickel slats ($NiSO_4$, Ni $(NO_3)_2$, $NiCl_2$) on black fish. Such studies are essential to push and regulate these toxic compounds.

NiO NPs properties

The properties of NiO NPs were examined using the instruments such as SEM, EDS, XRD, and XPS (Fig. 2). The SEM image showed that NiO NPs had a particle size of 15-35 mm with spherical morphology, specific surface area (SSA) of 50-100 square meter per gram (m^2/g), bulk density of 0.8 gram per cubic centimeters (g/cm^3), and true density of 6.67 g/cm^3. These structures were formed at a suitable calcination temperature (450 °C) which significantly affected the particle size and indicated that the particles had been dispersed satisfactorily in nanoscale size (Fig. 2a). EDS pattern of NiO NPs confirmed the presence of Ni (percent weight 73.2(, and O (percent weight 26). Concluding that the synthesized NiO NPs were made up of Ni and O with a molecular ratio of 1:1, no other trace elements were present (Fig. 2b). Fig. 2c shows that XRD patterns of NiO NPs have crystalline structure. The diffraction peaks at 37.23°, 43.15°, 62.12°, 75.21° and 78.55° were attributed to the diffraction plates of 111, 200, 220, 311, and 222 in NiO, respectively (ICSD card no. 01-071-2194, Jabeen *et al.,* 2020). Figs. 2d and e illustrate XPS of NiO in samples, and also Ni 2p1/2, Ni 2p3/2, and O 1s binding energies. Ni 2p3/2 peak appearing at 855.6 eV complied with NiO findings. The peak of O 1s at 530.7 eV was attributed to O_2 in NiO (Salavati-Niasari *et al.,* 2009).

Acute toxicity

$LC_{50\text{-}96h}$ values for NiO NPs, $NiSO_4$, $Ni(NO_3)_2$, and $NiCl_2$ are reported in Table 1. NiO NPs ($LC_{50\text{-}24h}$ = 575.5 mg/L) had the highest toxicity during the initial 24 hours of exposure, and $NiCl_2$ had the highest toxicity ($LC_{50\text{-}96h}$ = 91mg/L) after a 96-hour exposure. LC_{50} of different Ni compounds decreased with time, but toxicity of different Ni compounds, especially $NiCl_2$, increasd with time lapse from 24 to 96 hours. Overall, black fish was more sensitive to Ni salts rather than NiO NPs. The specific metal species can also impact toxicity. In addition, fish tolerance and/or resistance to environmental changes play a significant role in toxicity of chemicals. For example, *Rutilus rutilus* and *Carassius auratus* exposed to silver nanoparticles

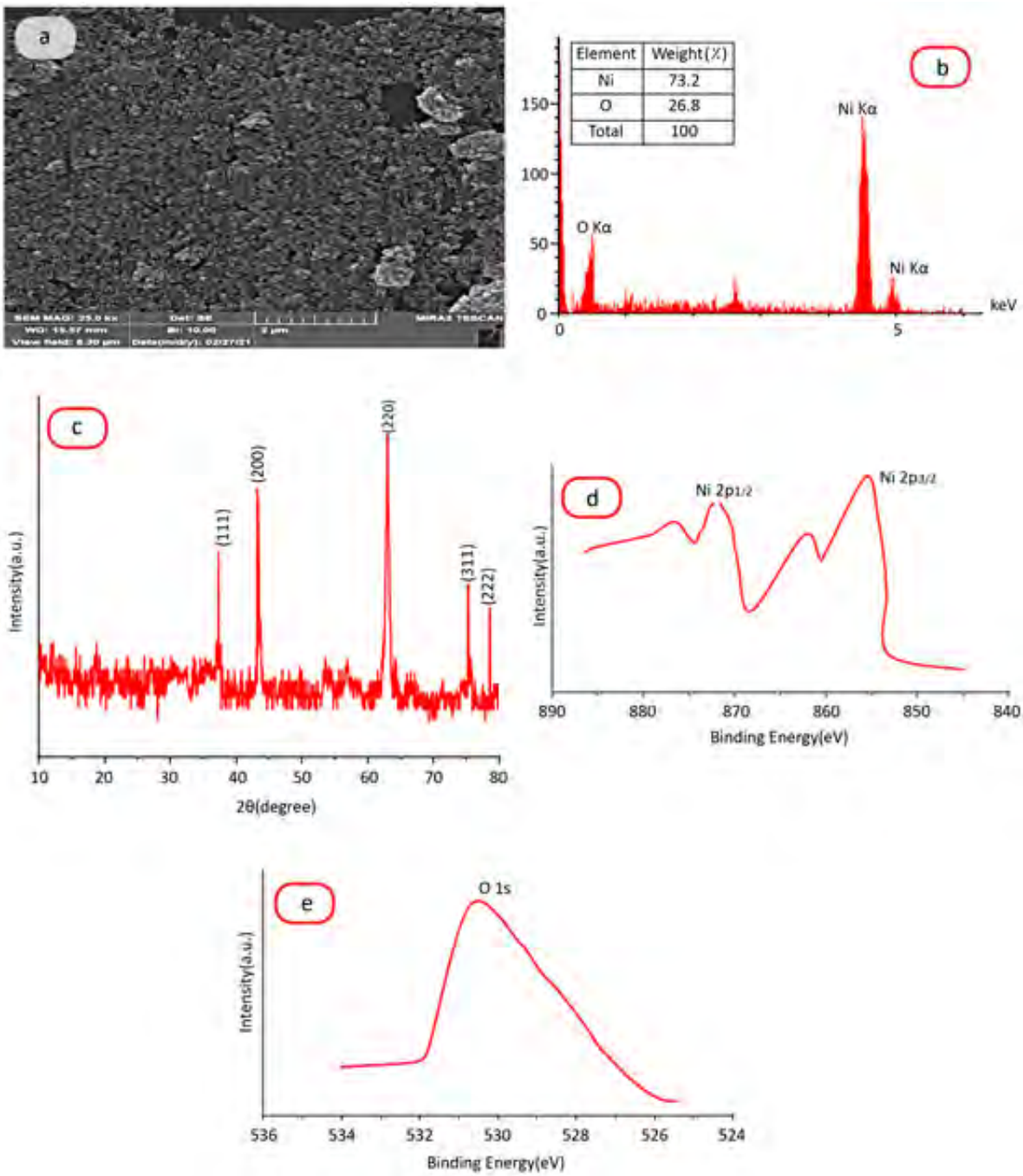

Fig. 2: Scanning Electron Microscopy (SEM) image for NiO NPs (a) , and patterns of X-ray Spectroscopic (EDS) (b), X-ray diffraction (XRD) (c), and X-Ray photoelectron Spectra (XPS) of Ni 2p (d) and O1s NiO NPs (e)

(Ag NPs) exhibited a drastically different $LC_{50\text{-}96h}$ (Yalsuyi and Vajargah, 2017). Compared to large-scale compounds, the metals in nano scale move across cell membrane and in the environment with more ease. This characteristic of NPs increases exposure and can lead to higher toxic effects (Boran and Saffak, 2018).

Table 1: Lethal Concentration (LC) of NiO NPs and nickel salts in black fish (*Capoeta fusca*)

NPs/salts	LC	Concentration (mg/L)			
		24 h	48 h	72 h	96 h
NiO NPs	LC_{50}	575.5	302	282	195
$NiSO_4$	LC_{50}	1862	371.5	155	120
Ni $(NO_3)_2$	LC_{50}	2884	219	182	138
$NiCl_2$	LC_{50}	1071.5	199.5	182	91

Higher toxic effects of Ni NPs compared to Ni salts was expected. However, Ni salts were much more toxic than NiO NPs to the fish. LC_{50} of all nickel compounds decreased with the increase of time from 24 to 96 hours, but its toxicity increased with time, since a lower concentration of nickel compounds caused death to the fish as it has been documented in other studies. Zinc oxide nanoparticles and graphene (a carbon-based nano material) toxicity to black fish increased with the increase of time from 24 to 96 hours (Sayadi *et al.,* 2021). In similar a study, Sayadi *et al.* (2020) stated that $LC_{50\text{-}96h}$ values of iron oxide nanoparticles (Fe_3O_4 NPs), iron nitrate ($Fe(NO_3)_3$), iron chloride ($FeCl_3$) and iron sulfate ($FeSO_4$) salts in blackfish were 32.3, 1.6, 2.3 and 2.5 mg/L, respectively. Based on these findings, toxicity of iron nitrate ($Fe(NO_3)_3$) was higher than that of iron nanoparticles, iron chloride and iron sulfate. With the time lapse from 24 hours to 96 hours, when the fish were exposed to different iron compounds, the toxicity of the compounds, especially $Fe(NO_3)_3$, increased. Boran and Saffak (2018) stated that $LC_{50\text{-}96h}$ value of NiO NPs and $NiCl_2$ in fish larvae (Zebrafish) were 122.2 and 32.6 mg/L, respectively, and concluded that the toxicity of $NiCl_2$ was higher than that of NiO NPs. Ghosh *et al.* (2018) reported the $LC_{50\text{-}96h}$ values of nickel in crustacean (*Diaptomus forbesi*) and fish (*Cyprinus carpio*) as 5.43 and 14.70 mg/L, respectively, and found that *Cyprinus carpio* was more sensitive than *Diaptomus forbesi* to nickel.

Bioaccumulation and depuration trend of NiO NPs and nickel salts in black fish tissues

Gill, intestine, liver, and kidney tissues of the fish were examined to determine bioaccumulation and depuration trend of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$ (Fig. 3). It was found that the bioaccumulation of NiO NPs (intestine > kidney > liver > gill); $NiSO_4$ (kidney > liver > intestine > gill); $Ni(NO_3)_2$ and $NiCl_2$ (kidney >intestine > liver > gill) during their 7-to-28-day exposures had a downward trend. High accumulation of NiO NPs occurred in the intestine, and kidney showed the highest accumulation of $NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$. Gills accumulated the least amount of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ (Table 2). However, studies on toxicity and bioaccumulation of NPs and their metal salts show conflicting results. Some reports imply that, compared to nano forms, metal salts have higher absorption and toxicity (Sayadi *et al.,* 2020). While others suggest the opposite and assert that toxicity and accumulation in nano forms are higher (Wang *et al.,* 2015). Bioaccumulation of all the compounds in the fish tissue indicated that some were highly concentrated in the intestine (NiO NPs), while others accumulated more in the kidney ($NiSO_4$, Ni $(NO_3)_2$ and $NiCl_2$). Interestingly, although NiO NPs bioaccumulated more than $NiCl_2$, it was $NiCl_2$ that caused more tissue damage in the fish (Table 2). This could be due to sequestration of NiO NPs in the intestinal tissues (contributing to reduction of its toxicity), while the metal salts, which were not sequestered early on in the digestive tract, had time to circulate in the body and inflict more damage. High metabolic activity in intestine and kidney could be behind high accumulation rates of NiO NPs in these tissues. Studies on *Cyprinus carpio* confirm the findings of this study (Khoei, 2021). However, still some reports are conflicting in terms of what tissue is more prone to metal NP bioaccumulation. Results of this study matches those of other studies (Yin *et al.,* 2020). The depuration of NiO NPs, $NiSO_4$ and Ni $(NO_3)_2$ had a trend of intestine > gill > liver > kidney, and the depuration of $NiCl_2$ had a trend of intestine > kidney > liver > gill. In general, the highest depuration of NiO NPs, NiSO4, Ni $(NO_3)_2$ and $NiCl_2$ was in the intestinal tissue, the lowest depuration of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ was in the kidney tissue, and the lowest depuration of $NiCl_2$ was in the gill tissue of the fish (Table 2). The detection limit and relative standard deviation (RSD%) of graphite furnace atomic absorption instrument for nickel were 0.55 g/L and 2% respectively. In ecotoxicological studies, intestine is a suitable bioindicator tissue, reflecting dietary metal uptake (Mijosek *et al.,* 2021). The intestine was the main tissue where rapid depuration of all tested

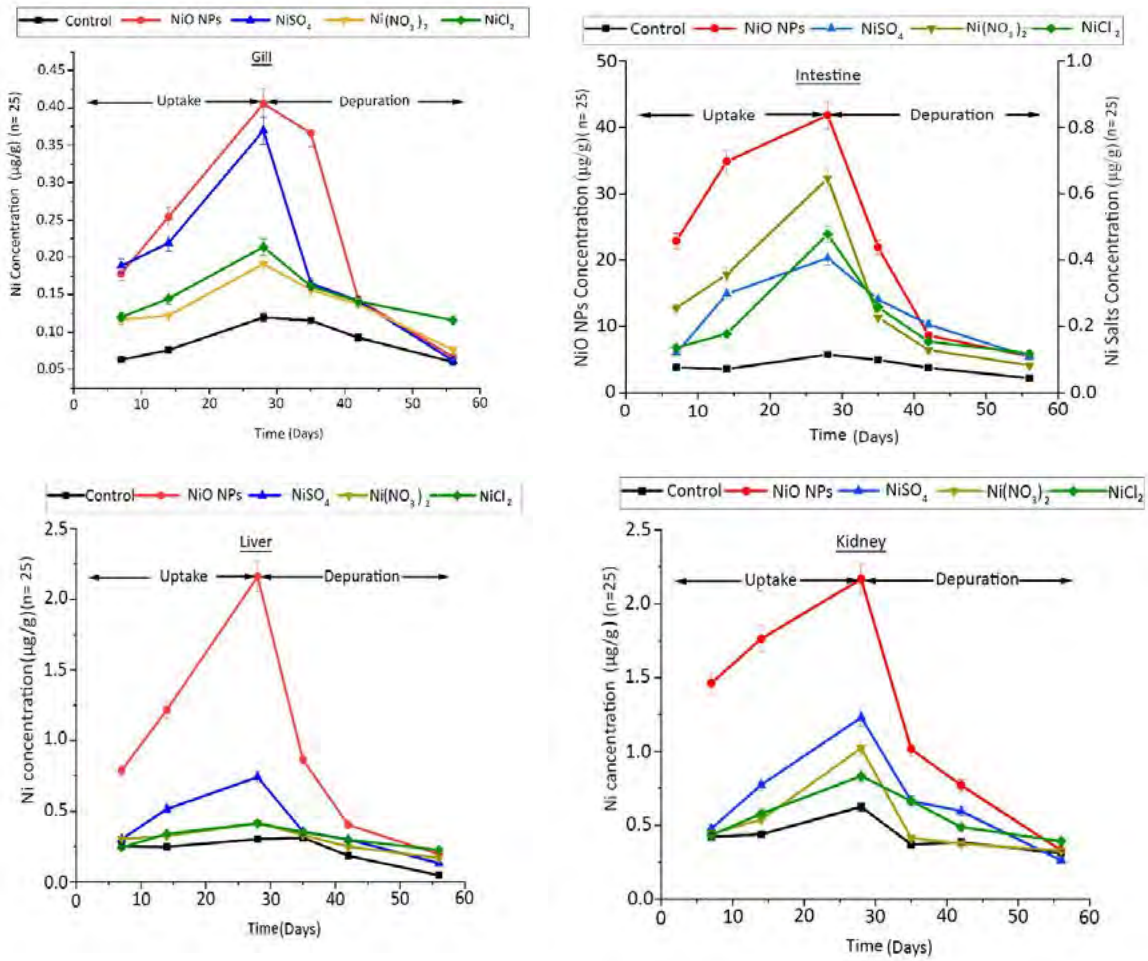

Fig. 3: Accumulation and depuration of Ni (µg/g) in gill, intestine, kidney, and liver of black fish (*Capoeta fusca*) exposed to NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ and $NiCl_2$

compounds occurred. Ni compounds, in this study, had a short biological half-life in the intestine of 1-2 days (Table 2), and intestinal sequestration and excretion of NiO NPs from this tissue were high. This phenomenon may be a protective mechanism in fish to reduce the exposure to toxicants. In addition, clean water can contribute to fish protection against Ni exposure since it facilitates depuration of this metal (Kalay and Canli, 2000). However, the available data suggest that intestinal depuration of NiO NPs depends, mainly, on its concentration and the duration of depuration (Sayadi *et al.,* 2020). Khoei (2021) reported that the highest bioaccumulation rate of occurred in liver and intestine tissues of fish (*Cyprinus carpio*), and it increased with the increase of Fe_3O_4 NPs and $FeCl_3$ concentrations. Sayadi *et al.* (2021) stated that the bioaccumulation pattern of ZnO NPs in different tissues of blac kfish was intestine> gill> kidney > liver. They also claimed that the bioaccumulation of ZnO NPs in different tissues of black fish increased with the increase of time. Hwang *et al.* (2016) stated that lead depuration trend in different fish (*Platichthys stellatus*) tissues with the increase of time from 4 weeks to 6 weeks was brain (85%)> muscle (79.1%)> intestine (69.1%)> spleen (66.5%)> liver (64.4%)> kidney (58.8%)> gill (49.1%).

Uptake and depuration kinetics of Ni

Kinetic parameters of Ni ion activity were examined and recorded using a one-compartment first-order model (Table 3). The uptake rate constant (K_1) and

Table 2: Bioaccumulation and depuration of Ni (µg/g) in gill, intestine, liver, and kidney tissues of black fish (*Capoeta fusca*)

Tissues	Time in Days	Bioaccumulation					Depuration				
		Control	NiO NPs	$NiSO_4$	Ni $(NO_3)_2$	$NiCl_2$	Control	NiO NPs	$NiSO_4$	Ni $(NO_3)_2$	$NiCl_2$
Gill (n=3)	7	0.06±0.04	0.17±0.08	0.18±0.08	0.11±0.07	0.11±0	0.11±0.04	0.36±0.10	0.16±0.01	0.15±0.03	0.16±0.03
	14	0.07±0.04	0.25±0.07	0.21±0.10	0.12±0.00	0.14±0	0.09±0.03	0.14±0.06	0.14±0.04	0.13±0.01	0.14±0.02
	28	0.11±0.02	0.40±0.08	0.36±0.04	0.19±0.01	0.21±0.12	0.05±0.02	0.06±0	0.06±0.01	0.07±0	0.11±0
p-value		0.07	0.0003*	-	-	0.04*	0.04*	-	0.07	0.04*	0.07
Intestine (n=3)	7	0.07±0.03	22.89±7.33	0.12±0.02	0.25±0.06	0.13±0	0.09±0.04	21.94±7.60	0.28±0	0.22±0.13	0.25±0
	14	0.07±0.01	34.88±7.11	0.29±0.15	0.35±0.07	0.17±0.01	0.07±0.04	8.67±1.11	0.20±0.06	0.12±0	0.15±0.02
	28	0.11±0	41.82±16.95	0.40±0.27	0.64±0.57	0.47±0.15	0.04±0	5.49±1.01	0.10±0	0.08±0	0.11±0
p-value		-	-	-	0.04*	-	0.07	-	0.03*	-	-
Kidney (n=3)	7	0.42±0.02	1.46±0.43	0.47±0.01	0.44±0.05	0.43±0.13	0.37±0	1.01±0.06	0.66±0.02	0.41±0.14	0.66±0.19
	14	0.43±0.04	1.76±0.47	0.77±0.05	0.53±0.12	0.57±0.11	0.38±0.15	0.76±0.67	0.59±0.01	0.37±0.11	0.48±0.10
	28	0.62±0.07	2.16±1.26	1.23±0.48	1.02±0.27	0.83±0.09	0.31±0.16	0.32±0.13	0.26±0	0.32±0.03	0.39±0.18
p-value		-	0.06	0.04*	-	0.02*	-	0.01*	-	0.07	-
Liver (n=3)	7	0.25±0.08	0.78±0.36	0.30±0.07	0.30±0	0.24±0.04	0.31±0.03	0.86±0.04	0.35±0.02	0.33±0	0.35±0.04
	14	0.24±0.18	1.21±0.43	0.51±0.07	0.32±0.07	0.33±0.05	0.18±0.03	0.40±0.25	0.30±0.02	0.24±0.04	0.29±0.01
	28	0.30±0.21	2.16±1.82	0.74±0.32	0.41±0.02	0.41±0.08	0.04±0	0.19±0.05	0.13±0.03	0.16±0	0.22±0
p-value		-	0.01*	-	0.09	-	-	-	0.04*	-	0.04*

(*) Statistical significance is indicated by an asterisk

the depuration rate constant (K_2) for $NiSO_4$ in gill were higher compared to other treatments, and it followed the pattern of NiO NPs > (Ni $(NO_3)_2$ and > $NiCl_2$. In the intestine and kidney, the highest uptake and depuration rate constants were observed in NiO NPs treatment group, and it followed the pattern of Ni $(NO_3)_2$ > $NiCl_2$ and > $NiSO_4$. In the liver, uptake and depuration rate constants pattern was NiO NPs > $NiCl_2$ > Ni $(NO_3)_2$ > $NiSO_4$. Since zero state stable equilibrium was obtained in all the treatments, the bioconcentration factor (BCF) was calculated using K_1 and K_2 ratio values. For all the tested compounds, the maximum BCF in gill, intestine and liver was in the following order: $NiCl_2$ > Ni $(NO_3)_2$ > $NiSO_4$ > NiO NPs. The maximum BCF in kidney followed the order of Ni $(NO_3)_2$ > $NiCl_2$ > $NiSO_4$ > NiO NPs, and the estimated time required for elimination half-life ($t_{1/2}$) of Ni was between 1 day for NiO NPs to 7 days for $NiCl_2$. In addition, the maximum BCF in gill, intestine, and liver followed the pattern of $NiCl_2$ > Ni $(NO_3)_2$ > $NiSO_4$ > NiO NPs. Kidney followed the different order of Ni $(NO_3)_2$ > $NiCl_2$>$NiSO_4$ > NiO NPs. It was also found that half-life ($T_{1/2}$) of nickel in black fish was between 1 day for NiO NPs to 7 days for $NiCl_2$ (Table 3). In a similar study, Sayadi *et al.* (2020) stated that the uptake rate constant K_1 and the depuration rate constant K_2 were higher in the intestinal tissue compared to the other tissues (*viz.* gill, liver and kidney) of black fish. They suggested that the maximum BCF for $FeCl_3$, Fe_3O_4 NPs and $FeSO_4$ groups was observed in the liver tissue and for Fe $(NO_3)_3$ group was observed in the gill tissue, whereas the lowest BCF occurred for $Fe(NO_3)_3$, $FeCl_3$ and $FeSO_4$ in the kidney tissue and for Fe_3O_4 NPs occurred in the intestinal tissue. They also stated that the approximate time required for elimination half-life ($T_{1/2}$) or iron in black fish was estimated to be between 15 days for Fe_3O_4 to 93 days for Fe $(NO_3)_3$. Comparison of these reports showed that Ni cleared from the black fish body much faster than Fe NPs. Mansouri *et al.* (2016) reported that the BCF value in the mixed treatment of copper oxide nanoparticles (CuO NPs) and titanium dioxide nanoparticles (TiO_2 NPs) was higher compared to the control group. Also, the highest BCF level for copper oxide nanoparticles was detected in liver > gill > intestine > muscle tissues. They also showed that the copper uptake rate increased in different tissues of common carp in the presence of titanium dioxide nanoparticles. López-Serrano Oliver *et al.* (2015) found that the BCF value of titanium ion was higher in 0.1 mg/L concentration than in 0.9 mg/L concentration, the BCF value of titanium dioxide nanoparticles was higher in 2 mg/L concentration than in 10 mg/L concentration, and the BCF value of titanium ion (Ti) was higher than that of TiO_2 NPs in Zebrafish embryonic fetus.

Physical and behavioral changes in exposed fish

Behavioral changes in black fish after 28 days of exposure to NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ and $NiCl_2$ are tabulated in Table 4. These findings confirm the earlier reports (Sayadi *et al.,* 2020). A guide to observed changes is provided as: -: none, +: 25%, ++: 50%, +++: 75% and ++++: 100% of black fish showed behavioral changes. In short, the fish exposed to $NiCl_2$, and Ni $(NO_3)_2$ exhibited "breathing at the surface" and "spiral swimming". The $NiCl_2$-exposed fish lost their coloration. NiO NPs exposure caused rapid gill movement and high mobility. The fish exposed to $NiSO_4$ exhibited weakness and lethargy. It swam in spirals and around air pockets. The fish behavior was negatively impacted by exposure to water contaminants. It has been argued that damage to fish organs and tissues result in such behavioral anomalies (Kienle *et al.,* 2008). This knowledge has even allowed us to use fish behavioral anomalies as a marker of water contamination level (Li *et al.,* 2014). The fish exposed to Ni compounds in this study exhibited a range of behavioral anomalies including rapid gill movement, surface breathing, mucus secretion on the gill surface, lethargy, and imbalance. Increased time of exposure resulted in intensified levels of such abnormalities (Table 4). Gill is the first tissue to be exposed to water contaminants. Rapid gill movement is due to fish hypoxia which occurs as a result of pollutant exposure (Sloman *et al.,* 2003). Continuous exposure to contaminants leads to higher mucus production and secretion in gill tissue, a protective response which would cause hypoxia if prolonged. These findings have been approved by others who reported rapid swimming, loss of balance, seizure, and increased fish activity in TiO_2 NPs-contaminated waters (Pirsaheb *et al.,* 2019).

Damage to gill and intestinal tissue

Severe histopathological lesions were caused by exposure to Ni compounds in gill and intestinal tissues (Figs. 4 and 5). The extent of tissue alteration was measured by Axio Vision Real 4.8 software compared to the control and the data were presented qualitatively. The fish exhibited fusion of lamellae, lamellar synechiae, curvature and oedema. $NiCl_2$ exposure of gill caused the highest rate of lamellar synechiae and curvature.

Table 3: Bioaccumulation and depuration kinetics of Ni in gill, intestine, kidney, and liver of black fish (*Capoeta fusca*)

	Gill				Intestine			
Parameters	NiO NPs	$NiSO_4$	$Ni(NO_3)_2$	$NiCl_2$	NiO NPs	$NiSO_4$	$Ni(NO_3)_2$	$NiCl_2$
K_1	0.21±0.03	0.24±0.04	0.11±0.02	0.09±0.01	0.62±0.43	0.29±0.06	0.37±0.07	0.36±0.07
K_2	0.01±0	0.01±0	0.005±0	0.004±0	0.030±0.019	0.012±0.002	0.015±0.002	0.013±0.002
$T_{1/2}$	3.27	2.87	6.42	7.88	1.11	2.38	1.85	1.89
BCF	16.3	17.21	21.60	22	23.00	24.25	24.93	28.15
	Kidney				Liver			
K_1	0.51±0.12	0.23±0.04	0.44±0.07	0.35±0.07	0.67±0.12	0.25±0.04	0.31±0.05	0.37±0.07
K_2	0.02±0	0.01±0	0.01±0	0.01±0	0.03±0	0.01±0	0.01±0	0.01±0
$T_{1/2}$	1.34	2.99	1.55	1.94	1.03	2.78	2.25	1.84
BCF	19.89	23.20	31.85	29.83	21.50	24.90	25.66	26.86

K_1: uptake kinetic constant (l/kg/day); K_2: elimination kinetic constant (1/ day); $T_{1/2}$: half-life (days); BCF: bioconcentration factor.

The maximum histopathological anomalies, fusion of lamellae, occurred when the fish were exposed to NiO NPs (Table 5). Fusion of lamellae and lamellar synechiae were observed in gill of the fish exposed to $NiSO_4$ and Ni $(NO_3)_2$ (Fig. 4). Gas exchange and osmotic regulation occur in the gill where pollutants first come into contact with the organism and can therefore be absorbed (Capaldo *et al.,* 2019). Fish gills are highly sensitive to exposure to environmental contaminants, since the respiratory epithelium has a large surface area and a high perfusion rate that facilitates the entry of pollutants into the gill (Santos *et al.,* 2014; Aghamirkarimi *et al.,* 2017). For this reason, gill's morphological changes, caused by toxic compounds, are widely used in biomonitoring of metal toxicity. Compared to NiO NPs, $NiCl_2$ caused much more severe damage to the

Table 4: Behavioral changes in black fish (*Capoeta fusca*) after exposure to NiO NPs, $NiSO_4$, Ni $(NO_3)_2$ and $NiCl_2$. None (-), Mild (+), Moderate (++) and Severe (+++)

Parameter	Control	NiO NPs	$NiSO_4$	Ni $(NO_3)_2$	$NiCl_2$
Hitting the wall of the aquarium	-	++	++	++	+++
Lightening of body color	-	+	++	+	+++
Rapid opening and closing of the gills	-	++++	+++	++	+++
Sleeping on back	-	++	+	+	+++
Loss of the ability to navigate in water	-	+	+	+	++
Swimming and high activity	-	+++	+	++	+++
The lack of balance	-	+	++	+	++
Mucus secretion	-	++	+	++	+++
Swim around the air rocks	-	++	+++	++	+++
Breathing from the water surface	-	+	++	++	+++
Sudden spins	-	+	+	+	++
Spiral swimming	-	++	++++	++	+++
Weakness and lethargy	-	+	++++	++	++
Protruding eyes	-	-	-	-	++

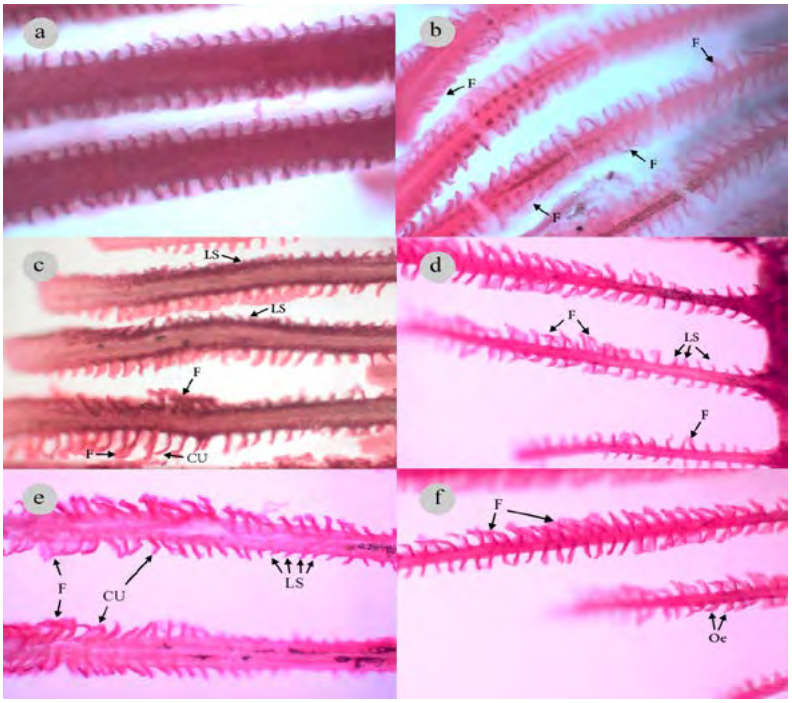

Fig. 4: Gill morphology in control (a) and black fish (*Capoeta fusca*) chronically exposed to nickel compounds: NiO NPs (b), $NiSO_4$ (c), Ni $(NO_3)_2$ (d), and $NiCl_2$ (e) (f). The injuries documented are: fusion of lamellae (F), lamellar synechiae (LS), curvature (CU), and oedema (Oe).

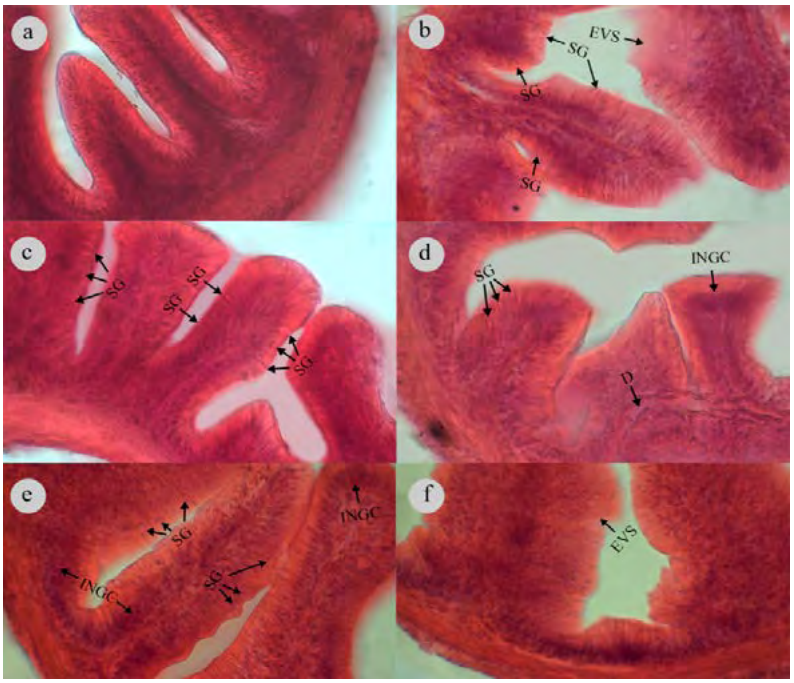

Fig. 5: Intestinal tissue of black fish (*Capoeta fusca*) exposed to NiO NPs and nickel salts (X400); Control (a), NiO NPs (b), $NiSO_4$ (c), Ni $(NO_3)_2$ (d), and $NiCl_2$ (e) (f). The injuries documented are: swelling of goblet cells (SG), higher number of goblet cells (INGC), degeneration of villi structure (D), and expansion at villi structure (EVS).

fish gill (fusion of lamellae, lamellar synechiae and gill curvature) and intestine. The curvature and adhesion of epithelium in gill's secondary lamellae is often the first sign of toxic effects. Fusion of lamellae is caused by cellular proliferation that gradually fills the space between gill layers (Mansouri *et al.,* 2016). Similar to mucosal secretion, fusion of gill lamellae is a protective mechanism to help limit exposure and tissue damage (Beegam *et al.,* 2020). The findings comply with results reported by others showing that hyperplasia, fusion of lamellae and aneurism in fish are due to the exposure to TiO_2 NPs, ZnO NPs, ZnO NPs and Cu NPs (Pirsaheb *et al.,* 2019; Sayadi *et al.,* 2021). Additive toxic effects of Fe on TiO_2 NPs and reduced toxicity of ZnO NPs when combined with NGs have been reported by the same authors. In the control group, intestinal structure was normal, and epithelia and Goblet cells were properly arranged. After 28 days of exposure to NiO NPs and nickel salts, swelling of Goblet cells (SG), increased number of Goblet cells (INGC), degradation (D), and expansion at villi structure (EVS) were observed. The highest rate of these abnormalities occurred when the fish were exposed to $NiCl_2$. However, the gill and intestine abnormalities were much higher in the fish exposed to nickel salts than in the fish exposed to NiO NPs (Fig. 5). It was not possible to study histopathology of the fish intestine exposed to NiO NPs because the tissue had been destroyed. Intestine plays an important role in braking down of the environmental chemicals, and there is clear evidence that metabolism of pollutants modulates the toxicity for the host, emphasizing the protective role that intestine plays against toxic exposures. Moreover, pathophysiological changes in the gastrointestinal tissue caused by ingestion of toxins, have led to systemic adverse effects (Claus *et al.,* 2017). The intestinal epithelium consists of a mucosal layer with villi that synthesizes and secretes mucin and a goblet cell layer (Cheng, 1974). Mucin plays a critical role in trapping toxicants, particularly metals. The results showed the severe damage to the intestinal tissue of the fish. Compared to NiO NPs, $NiCl_2$ was more damaging to the intestinal tissue and the tissue lesions became progressively worst in time. $NiCl_2$ exposure led to goblet cell hypertrophy and swelling. Goblet

Table 5: Semi-quantitative evaluation of lesions recorded in the gill and the intestine of black fish (*Capoeta fusca*) exposed to NiO NPs and nickel salts

Tissues	Histopathological changes			
Gill	**Oe**	**LS**	**F**	**CU**
Control	-	+	-	-
NiO NPs	+	+++	+	-
$NiSO_4$	+	++	++	-
$Ni(NO_3)_2$	-	++	++	-
$NiCl_2$	++	++	+++	+
Intestine	INGC	EVS	D	SG
Control	-	-	-	-
NiO NPs	-	+	-	+++
$NiSO_4$	-	-	-	+++
$Ni(NO_3)_2$	++	-	+	++
$NiCl_2$	++	++	-	+++

Odema (Oe), Lamellar synechiae (Ls), Lamellar fusion (F) and Curvature (CU) in gill; and Swelling of Gobletcells (SG), Degeneration (D), Expansion at Villi Structure (EVS), and Increase in the Number of Goblet Cells (INGC) in intestine. None (-), Mild (+), Moderate (++) and Severe (+++)

cell hypertrophy is described as the first protective response to toxic exposure, and it can temporarily reduce toxic effects. The findings confirm the results of other studies showing the intestinal damage as a result of exposure to metal NPs (Kakakhel *et al.,* 2021). Liu *et al.* (2019) reported that cadmium caused histopathological lesions erosion of villi, necrosis in the mucosal layer, hyperplasia and swelling of goblet cells in the fish (*Carassius auratus*). They demonstrated that the severity of anomalies increased with the increase in the cadmium concentration. Rahmani *et al.* (2019) reported that mercury and Ag NPs increased the number of goblet cells and swelling of goblet cells in the intestine of fish (*Cyprinus carpio*). Pirsaheb *et al.* (2019) reported the histopathological anomalies caused by titanium oxide nanoparticles in the intestinal tissue of fishes (*Carassius auratus*) and (*Cyprinus carpio*) as necrosis and erosion, degeneration, increase in the number of goblet cells, swelling of goblet cells, and increase in the number of lymphocytes.

CONCLUSION

In recent years, nanoparticles are widely used in many fields and various sectors such as electronics, textiles, cosmetics, medical equipment, and food packaging. They are considered as a serious threat to the environment due to their toxicity. Based on chemical composition, nanoparticles can be divided into different groups such as metal nanoparticles, polymer metal oxide, semiconductor, and metal oxide. Among the metal oxide group, NiO NPs, due to their properties, are widely used in many industrial and commercial products such as solar cells, conductive coating, fuel cells, catalytic converters in cars, and biosensors. NiO NPs have low solubility and high stability in water, so that it can remain in solid form in water and attach to other particles or aquatic organisms. After entering the water, NiO NPs can be eaten by organisms or attached to their external organs or absorbed by their internal membranes, causing direct toxicity. Despite the increased use of nanomaterials in various sectors, few studies are available on the health effects and toxicity of these materials on organisms. Therefore, this study attempted to use biological indicators in monitoring and controlling the environmental pollution, since these substances eventually enter the aquatic environment. When there is a specific concentration of pollutant in the environment and this amount does not cause death, it can cause changes in the tissues and cells of organisms. The use of tissue pathology method with the help of light microscope is one of the useful ways to detect the amount of damage to the tissue caused by the environmental factors such as metals and nanomaterials. Tissue pathology can provide a correct assessment of the health of the target tissue in living organisms and reflects the effects of exposure to environmental pollutants. Intestinal and gill tissues are among the pollutant-absorbing tissues that contain a high concentration of toxic substances. The purpose of this study was to investigate the toxicity of NiO NPs compared to different nickel salts. The acute toxicity of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$ on black fish (*Capoeta fusca*) was investigated. To explore the chronic toxicity of NiO NPs and Ni salts, first the fish were exposed to NiO NPs and its salts for 28 days to determine the amount of bioaccumulation of

various Ni compounds in gill, intestine, liver and kidney tissues. Then, the fish were placed in clean water for 28 days to calculate the rate of depuration of various Ni compounds. Various changes in hematological, biochemical and liver enzymes parameters were investigated in the fish. $LC_{50\text{-}96h}$ values for NiO NPs and salts of $NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$ were reported as 194.98, 120.22, 138.03, and 91.20 mg/L, respectively. The results showed that $NiCl_2$ was more toxic than NiO NPs, $NiSO_4$, and Ni $(NO_3)_2$. Moreover, NiO NPs had the highest bioaccumulation rate in gill tissues (0.40 ± 0.08 µg/g), intestine (41.82 ± 16.95 µg/g), liver (2.16 ± 1.82 µg/g g) and kidney (2.16 ± 1.26 µg/g). Exposure of the fish to NiO NPs and its salts caused histopathological damage such as swelling of goblet cells, increase in the number of goblet cells, destruction, and expansion of the villi structure in the intestine. The amounts of white blood cells, hemoglobin and hematocrit of the fish exposed to Ni $(NO_3)_2$ were higher compared to the control group, showing that they had polycythemia. Changes in the erythrocytes structure (deformed erythrocytes, nuclear disintegration, and micronucleus) were observed in the fish exposed to various Ni compounds. Biochemical factors in the fish blood, such as cholesterol, glucose, creatinine and uric acid, were higher compared to the control group. Liver enzymes ALP, AST and ALT blood of the fish exposed to various Ni compounds were significantly ($p < 0.05$) higher as compared to the control group, showing that the liver tissue was damaged. All the tested compounds bioaccumulated in the fish tissue, some with higher concentrations in the intestine (NiO NPs), and others with higher accumulation in the kidney ($NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$). The depuration of NiO NPs, $NiSO_4$, and Ni $(NO_3)_2$ followed the trend of intestine > gill > liver > kidney, and the depuration of $NiCl_2$ followed the trend of intestine > kidney > liver > gill. The highest depuration of NiO NPs, $NiSO_4$, Ni $(NO_3)_2$, and $NiCl_2$ was in the intestinal tissue, the lowest depuration of NiO NPs, $NiSO_4$, and Ni $(NO_3)_2$ was in the kidney tissue, and the lowest depuration of $NiCl_2$ was is in the gill tissue of the fish. The gill and intestine were found to be the most vulnerable tissues in the fish exposed to Ni contaminants. $NiCl_2$ exposure of gill caused the highest rate of lamellar synechiae and curvature. The maximum histopathological anomalies, fusion of lamellae, occurred when the fish were exposed to NiO NPs. The results showed that compared to NiO NPs, $NiCl_2$ was more damaging to the intestinal tissue of the fish, and the tissue lesions became progressively worst in time. The obtained results imply the necessity for the relevant organizations to specify limits for the amount of different nanoparticles, especially nickel, entering into the water environments. It is suggested to study the toxicity effects of multi metals in aquatic organisms in a real environment (according to mutual effects on each other) on other tissues such as skin and muscle in different environmental conditions such as pH, hardness, salinity and temperature.

AUTHOR CONTRIBUTIONS

J. Kharkan conducted the conceptualization, study design, field work, data analysis, and writing of the first draft. M.H. Sayadi performed the project administration, funding, conceptualization, review, and some rewriting of the first draft. M. Hajiani did the field work, data analysis, and feedback. M.R. Rezaei participated in the interpretation of the results and manuscript preparation. M. Savabieasfahani made a significant contribution to data illustration, enhancing the discussion section, and rewriting of the manuscript in proper English.

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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

%	Percent
BCF	Bio-concentration factor
CU	Curvature
Cu NPs	Copper nanoparticles
D	Degeneration of villi structure
EDS	Energy dispersive spectroscopy
EVS	Expansion at villi structure
F	Fusion of lamellae
Fig	Figure
Fe_3O_4 *NPs*	Iron oxide nanoparticles
$FeCl_3$	Iron chloride
$FeSO_4$	Iron sulfate
$Fe(NO_3)_3$	Iron nitrate
g/L	Gram per liter
g/cm^3	Gram per cubic centimeter
INGC	Higher number of goblet cells
K_1	Uptake rate constant
K_2	Depuration rate constant
LC_{50}	Lethal concentration 50
LD_{50}	Lethal dose 50
LSC	Lower sub-lethal concentration
LS	Lamellar synechiae
mg/L	Milligram per liter
mL	Millilitre
m^2/g	Square meter per gram
NiO NPs	Nickel oxide nanoparticles
$NiSO_4$	Nickel sulfate
$Ni(NO_3)_2$	Nickel nitrate
$NiCl_2$	Nickel chloride
NPs	Nanoparticles
Ni	Nickel
N	Number
NGs	Graphene nanoparticles
Oe	Oedema
RSD	Relative standard deviation
SEM	Scanning electron microscopy
SG	Swelling of goblet cells
SSA	Specific surface area
$T_{1/2}$	Half-life
TiO_2 *NPs*	Titanium dioxide nanoparticles
XRD	X-ray diffractive
XPS	X-ray photoelectron spectra
ZnO NPs	Zinc oxide nanoparticles
µg/g	Micrograms per gram
µm	Micrometer
µS/cm	Microsiemens per centimeter

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ORIGINAL RESEARCH PAPER

Land use variation impacts on trace elements in the tissues and health risks of a commercial fish

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ABSTRACT

BACKGROUND AND OBJECTIVES: Tropical coastal ecosystems globally have been affected by land use changes. This condition has caused a discharge of pollutants into the water, affecting marine organisms, including fish. Due to their habitat preferences, fish are prone to elevate heavy metals in their tissue. Considering fish is consumable, heavy metal levels in fish can lead to health risks. One of the common edible fish in Southeast Asia is Pennahia argentata. Although widely consumed, there is limited information on how land use influences heavy metal levels in various tissues of this species and its health risk. Fish is one of the main food sources in this region, indicating this information's importance. This study aims to elaborate on and differentiate the heavy metal levels in tissues and land use types, including settlement and mangrove areas on the West Java coast of Indonesia.
METHODS: Locations of this study are the Jakarta coast representing anthropogenic influences in the form of settlements and the Subang coast as a site of mangrove covers. This study combined remote sensing and Geographic Information System analysis with heavy metal analysis using inductively coupled plasma and studied heavy metals, including cadmium, copper, and zinc, in fish tissues such as the gill, digestive tract, and muscle. Differences and correlation of heavy metal data in each tissue and location were statistically analyzed using Pearson correlation values (r), Analysis of Variance, and x2-test. The estimated Daily Intake was used to determine the health risk consumption of this species.
FINDINGS: All levels of heavy metals are below the World Health Organization's permissible limits. Zinc is consistently high in all tissues and locations, while cadmium is the lowest. The result shows that the digestive tract consistently has the highest heavy metal levels compared to other tissues in both locations. Heavy metal in muscle has the lowest level. Copper and zinc in the muscles of fish living on the settlement coasts were 62.69% and 37.18% higher ($P < 0.05$) than fish inhabiting mangrove coasts.
CONCLUSION: Trace elements in the commercial fish P. argentata were significantly affected by differences in land use. Variations in land use have elevated heavy metal levels in fish tissues. Given the high levels of heavy metals, the digestive tract can be chosen as a specific fish tissue to be used as a bioindicator to monitor cadmium, copper, and zinc, particularly on the West Java coast in Indonesia. Because the Estimated Daily Intake for zinc in Jakarta is high, consuming fish should be done with caution.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
75	6	4

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INTRODUCTION

Southeast Asia is well known for having lucrative tropical coastlines with a major diversity of fish. Genus *Pennahia* of Sciaenidae (Huang *et al*., 2022) is among the most abundant commercial species in Asian water. Silver croaker or scientifically known as *Pennahia argentata* (Houttuyn, 1782) (Wang *et al*., 2018), is considered a high economic-value fish species (Yamaguchi *et al*., 2006). Fish consumption per capita in Indonesia is estimated to increase in 2024, 2025, 2026, 2027, and 2029. Among those fish species, *P. argentata* is one important commercial fish in Indonesia's coastal water (Alfian *et al*., 2020). This species is accounted for 3.36% of fish caught in Malela waters, Awangpone subdistrict, Bone district, Indonesia, equal to 10.42 kg (Patangngari *et al*., 2022). *P. argentata* was also inhabiting coastal ecosystems on Java island (Murhandini *et al*., 2022). A recent study by Takarina *et al*. (2022) confirmed that *P. argentata* individuals dominated the fish community, particularly in West Java coastal waters. Kirab *et al*. (2021) recorded that abundances of *P. argentata* accounted for 1557.3 kilograms per square kilometer (kg/km^2). According to Partasasmita *et al*. (2015), the West Java coast's coastal ecosystems are known to have a high fish species population, including families of Arridae (*Netuma thalassina*), Bothidae, Clupeidae, Haemulidae, Leiognathidae (*Leiognathus* spp.), Nemipteridae (*Nemipterus hexodon*), Plotosidae, Sciaenidae (*Pennahia* spp.), and Synodontidae *(Saurida tumbil*). Despite growing research on *Pennahia argentata*, the information about heavy metal levels in this species is still very limited. Coastal ecosystems are subjected to several anthropogenic activities. Anthropogenic disturbances caused by some activities, such as agriculture (Nuryanto *et al*., 2021), massive urbanization, and mangrove deforestation (Fabinyi *et al*., 2022), may contribute to the increasing levels of heavy metals. Because of anthropogenic activities in the coastal ecosystems that discharge heavy metals to the ecosystems, several commercial fish species have been reported to contain metals in their tissues. In Bangladesh on the Meghna coast (Ahmed *et al*., 2019), the edible tissues of *Aila coila, Clupisoma garua*, *Latis calcarifer*, *Otolithoides pama*, *Planiliza subviridis*, *Rhinomugil corsula, Silonia silondia*, and *Tenulosa ilisa* were known containing arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), and lead (Pb). *Johnius belangeri* and *Arius thalassinus* species in coastal waters of Kapar and Mersing, Malaysia, were reported to have high Zn with ranges of 13.12–739.6 µg/g (Bashir *et al*., 2013). Salam *et al*. (2019) reported that the consumed fish species in Tok Bali Port, Kelantan coast, Malaysia contained heavy metals (Zn, Pb, Ferro (Fe), Cd, and Cu) with an order of rarely consumed species according to the heavy metal accumulation is as follows *Descapterus macrosoma* < *Pampus argenteus* < *Leiognathus daura* < *Euthynnus affinis* for Cd and Pb, *Pampus argenteus* < *Descapterus macrosoma* < *Euthynnus affinis* < *Leiognathus daura* for Fe, *Leiognathus daura* < *Descapterus macrosoma* < *Pampus argenteus* < *Euthynnus affinis* for Cu, *Pampus argenteus* < *Descapterus macrosoma* < *Euthynnus affinis* < *Leiognathus daura* for Zn. Heavy metal levels were also reported in commercial fish on Indonesian coasts. In Barito and Donan coasts, Indonesia, several commercial fish contain metals. Cahyani *et al*. (2016) reported the Cd and Cu for edible *Silago sihama* were 0.56 and 1.39 miligram per kilogram (mg/kg), respectively, in Donan. On the Barito coast, the Cu levels for *Leiognathus brevirostris*, *Ophiocephalus striatus*, and *Rastrelliger kanagurta* were 0.01 mg/kg, 0.03 mg/kg, and 0.05 mg/kg. While the Cd levels were 0.03 mg/kg, 0.01 mg/kg, and 0.07 mg/kg (Dwiyitno *et al*., 2008). Despite Indonesia's coasts being enriched with fish resources, those coasts are recently threatened by the presence of land use conversion, and anthropogenic influences from intact mangrove forests converted to human settlements. In Indonesia, comprehensive studies of the heavy metal levels in fish species related to changes in coastal land uses are still lacking. At the same time, this information is needed as fish have commercial value and are consumed by nearby communities. According to Handayani *et al*. (2017), the West Java coast is disturbed by population density and anthropogenic activities that have caused land use changes and led to the fish community assemblages. Currently, the West Java coast has a population of 35 million, and this population keeps increasing. As a result, the West Java coast now has the second-largest urban population in the world (Octifanny and Hudalah, 2017) and can pose a significant threat to coastal fish resources. This condition has been confirmed by Takarina *et al*. (2022) that the numbers of fish species found at the threatened site, dominated by settlements, were lower than those at the intact site, dominated

by mangroves. More fish species are discovered at the intact location with Shannon-Wiener index (H') values of 2.17. The average fish species diversity, denoted as H' index, decreased by 53.91% from 2.17 in intact site (95% confidence interval [CI]: 1.15–3.19) to as low as one disturbed site (95% CI: 0.018–1.98) as a consequence of anthropogenic activities and presences of settlements. Since anthropogenic activities along with settlements will discharge heavy metals then, this study attempts to address the following questions, are there any variations in the heavy metal levels in commercial fish species between coast variations ranging from settlements and mangroves? If there is a difference, what fish tissue contains the heaviest metals? The results of this study can contribute significantly to prioritizing which land should be managed due to the heavy metal contamination in fish. The specific information on which tissue contains the heaviest metals will also significantly reduce the health risk (Ahmed *et al*., 2019) due to consuming contaminated fish by coastal communities nearby. The novel aspect of this study is the development and correlation of land use changes with the magnitudes of heavy metals in fish, as well as the potential health risks of consuming these contaminated fish. This identification of land use changes and heavy metal links will contribute significantly to pollution management and heavy metal monitoring. The current study aims to elaborate and differentiate the heavy metal levels in tissues and land use types, including settlement and mangrove areas on the West Java coast of Indonesia. This study aims to assess and compare the levels of the heavy metal, including Cd, Cu, and Zn, in gills, digestive tracts, and muscles of commercial fish *Pennahia argentata* (Houttuyn, 1782) inland uses dominated by settlements and mangroves in West Java coast on 2022.

MATERIALS AND METHODS

Study area

The study area was in West Java coastal areas, Indonesia, which consists of two locations, including Jakarta in the west and Subang in the eastern parts of the West Java coast. These sites were chosen as the research areas representing land uses dominated by settlement and mangrove covers (Fig. 1). The determinations of those locations were based on literature reviews, field observations, and satellite image classification using geographical information system (GIS) analyses. The settlement location was part of Jakarta city, with a geographical location between 6.103° and 6.108° (SL) south latitude and 106.773° and 106.779°(EL) east longitude. Due to the conversion of the natural mangrove vegetation into settlements, the settlement site is recognized by the absence of natural cover, particularly mangrove forests. Driven by high population and economic growth, Jakarta has had massive residential developments (Suliman *et al*., 2022). As a result, settlement (Franjaya *et al*., 2017) has disturbed the intact mangrove forest cover in Jakarta, decreasing mangrove areas from 1998 to 2018 by up to 393 hectares (Fig. 2) (Rizal and Haykal, 2021). Traditional fishermen continue to use the water off the shore to catch some fish species despite these significant anthropogenic impacts. The mangrove land use locations followed the previous research location (Takarina *et al*., 2022). The mangrove site was in the Subang district, with coordinates of 6.241°SL and 107.667° EL. Site land uses are characterized by a matrix of fish ponds with intact mangrove forests and reforested mangroves. Lucrative mangrove covers previously characterized this site. Even though those intact mangroves were experiencing deforestation and transformed into fishponds. However, led by fishermen and community awareness, the threatened mangrove forest has been rehabilitated through mangrove plantings. As a result, now there were mangrove covers combined with fishponds. The surrounding water near the coast is known to have various fish species of commercial value that are edible or can be used as a food commodity.

Fish survey and collection

Fish survey procedures were followed and adapted from previous studies (Takarina *et al*., 2022) with additional references from Agustriani *et al*. (2020) and Araújo *et al.* (2006). The survey was conducted in the morning from 8.00 am to 2.00 pm. Gillnet, with a mesh size of 2 inches, was used to capture fish. The collected fish were preserved using ten percent (%) formaldehyde. The morphological character using the identification key provided in the guidebook of fish identification was performed to identify fish species (Kottelat and Whitten, 1993). The collected fish were adult fish with body lengths measuring more than 10 cm since adult fish contain trace elements.

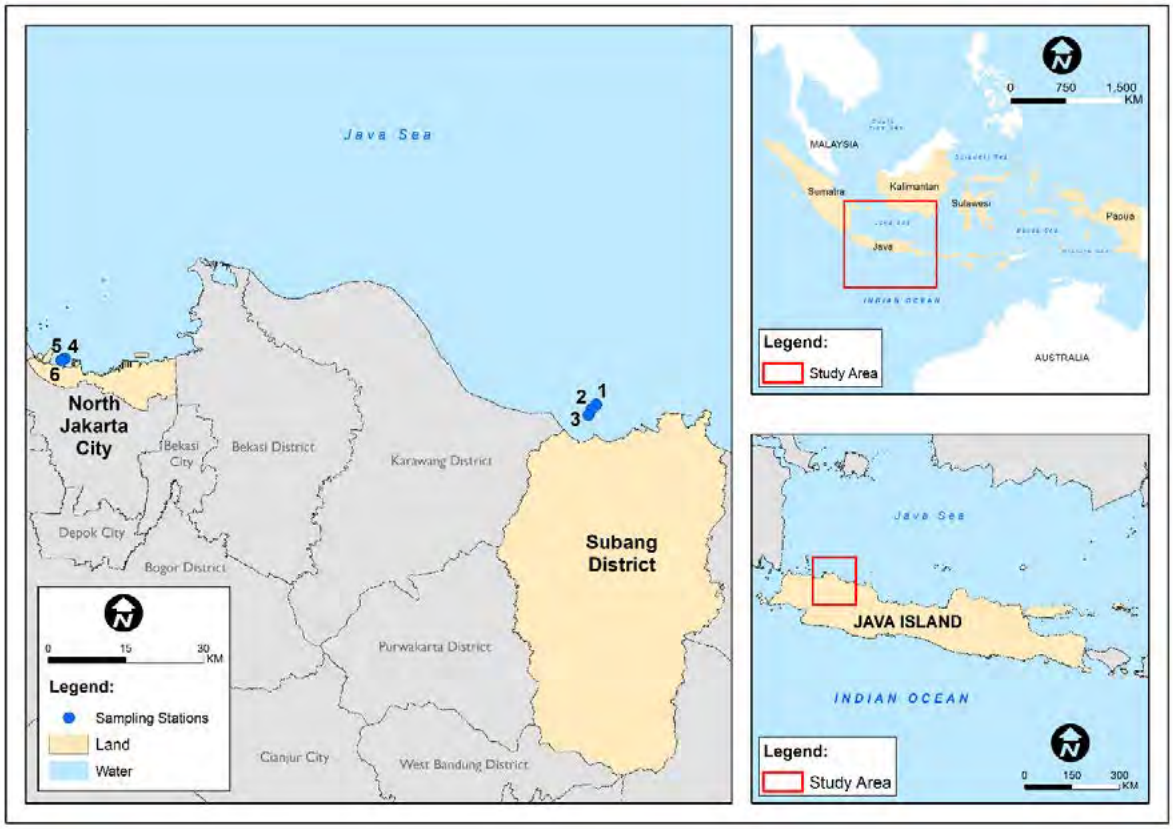

Fig. 1: Geographic location of the study area in Indonesia's West Java coast, with Subang district in the east and Jakarta city in the west dominating settlements and mangroves, respectively

Fish tissue heavy metal preparation and measurements

In each location, ten individuals of silver croakers were collected. The silver croaker samples were primarily retained in the zip-locked acid-washed polyethylene bags at −20°C to prevent deterioration and finally delivered to the laboratory for further heavy metal analysis processing. Surgical equipment was used to dissect each fish sample in the laboratory (Lakshamanasentil *et al*., 2012; Enuneku *et al*., 2018). The silver croaker's gills, digestive tract, and muscles were placed on sterile aluminum foil. Samples of silver croaker were then dried at 60 °C to eliminate water content until they had totally dried. After drying, the sample was finely powdered in a mortar. In a Teflon beaker containing 0.05g homogenized sample, 1.5 milliliter (mL) of Suprapur 65% nitric acid (HNO_3) was added to transform organometallic into an inorganic form. The sample in all Teflon bombs was heated in the oven digestive at 100°C for 8 hour (h). The sample was left to rest before the acid-digested solution was transferred into separate centrifuge tubes. Mili Q water was added until a volume of 10 ml was obtained (Poong *et al*., 2020). The resulting filtrate was submitted to inductively coupled plasma (ICP) (Nurhasanah *et al*., 2023) using a standard diluted sample solution for Cd, Cu, and Zn analyses. For each set of experiments blanks, samples were run, along with certified reference materials (CRMs), and corrections were applied where necessary. Each fish sample was examined in triplicate, and only average results were reported. The wavelengths used for the detection and measurement were as follows: Cd 214.440, Cu 324.752, and Zn 213.857 nm. The permissible limits for Cd, Cu, and Zn follow the threshold provided by WHO (Abdel-Baki *et al*., 2011).

Physico-chemical parameters measurements

Physico-chemical parameters such as the potential of

hydrogen (pH), salinity, and dissolved oxygen (DO) were recorded in situ. Each parameter was noted with three replications for each sampling location. The equipment used to measure the variables was a Lutron DO meter 5510 for DO value, a Lutron pH meter 5510 for pH, and an Atago refractometer for salinity, respectively.

Data analysis

Coastal land uses

The classification of land use changes in coastal areas representing settlement and mangrove land uses was done using GIS. Image captured using Landsat eight was then supervised and reacquired to obtain the type of land use. The categories for coastal land use classifications were mangrove and fishpond, water and sea, settlement, and mangrove. Then, the compositions of each lad use type were denoted as a percentage.

Health risk assessments

The estimated daily intake (E) of metals was estimated using Eq. 1 (Zhao *et al*., 2012).

$$E = \frac{metal\ levels\ x\ consumption\ rate}{body\ weight} \quad (1)$$

Where,

Metal levels: measured in mg/kg; Body weight: body weight was estimated to be 55.9 kg for adults and 32.7 kg for children; Consumption rate: consumption rate was assumed to be 93 g/day kg for adults and 50 g/day for children; E: estimated daily intake in µg/kg/day

Statistical analysis

Statistical analysis in this study consists of Pearson correlation values (r), analysis of variance (ANOVA), and x^2-test. Pearson test was used to assess the inter-heavy metal correlations in gill, muscle, and digestive tract tissue. ANOVA was used to test the differences in heavy metal levels between locations and tissues. While the x^2-test was utilized to examine the differences in land use compositions. Data were visualized using GIS-based thematic maps and jittered box plots.

RESULTS AND DISCUSSION

Coastal land uses

One important data collected during this research is the land use characteristics, which significantly influence heavy metal concentrations in fish inhabiting coastal habitats. According to the statistical findings, a significant difference in the compositions of land uses was discovered (x^2 = 23.532, P < 0.05). The order of coastal land use in the Jakarta site was settlement > water, as can be seen in Fig. 2. From 1998 to 2018, there were land use changes due to deforestation that caused land use conversion from intact mangrove forest to fishponds and settlements, as can be seen in Jakarta. There were six locations in Jakarta where land uses changes and deforestation occurred (Fig. 2). In contrast; settlements were rarely found at the Subang. At the Subang site, the order of land use was mangrove within fishponds > intact mangroves > water.

Heavy metal levels in P. argentata

Heavy metal levels in *P. argentata* in various tissues between varied land uses are available in Fig. 3. The general patterns were Cd, Cu, and Zn were more common in digestive tracts compared to muscle and gills. The heavy metal level orders for Cd, Cu, and Zn were digestive tracts > gills > muscles. For Cd, the heavy metal levels, particularly in gill tissues in settlement sites, were higher than in gill tissues in mangrove dominance sites. While Cd levels in mangrove dominance sites were higher than in settlement sites. For Cu and Zn levels, the heavy metal level orders were digestive tracts > gills > muscles for both settlement and mangrove dominance sites. For particular Zn levels, Zn in gill was considered dominant next to the digestive tract. Cu and Zn levels were observed to be higher in all tissues in Jakarta than in Subang, as can be seen in Fig. 4. This indicates land use changes increase both the Cu and Zn levels. The highest increase in heavy metal levels was observed for Cu for muscle tissues. The changes of mangroves to the settlement have increased Cu in the muscle up to 62.69%. For Cu, heavy metals were observed to be very high in samples from Jakarta in the digestive tract, equaling 74.42 ppb. Changes in mangrove forest settlement will significantly increase the Zn in muscle (P = 0.012) to 37.18%. For Zn, heavy metals were observed to be very high in samples from Jakarta in gill, equaling 751.53 ppb (Table 1).

Intercorrelations of all trace elements in the gill, digestive tract, and muscle are available in Fig. 5 for Jakarta sites and Fig. 6 for Subang sites. Regarding the correlation (Pearson correlation) values (r), it is obvious that there is a significant positive correlation

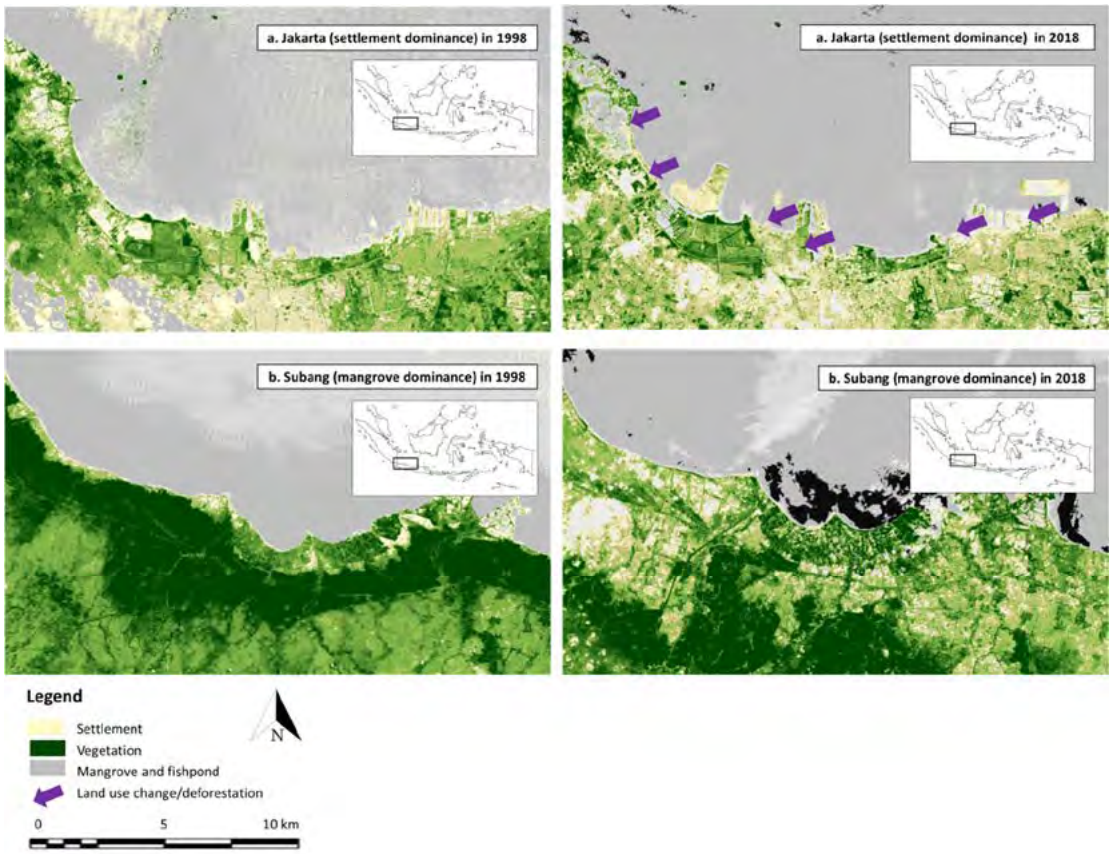

Fig. 2: Land use changes from 1998 to 2018 as indicated by arrows in Jakarta city in the west (settlement dominance) and Subang district in the east (mangrove dominance) on the West Java coast, Indonesia

between the trace elements found in the same tissues in Jakarta. The highest correlation was observed for the Cd concentration with the Cu in the digestive tracts (r = 0.87). The second significant correlation was observed for the Cd concentration with the Cu in the gills (r = 0.83). The relationships between inter-metal levels in various tissues were quite different, as observed in the Subang site. In this site with mangrove dominance, the highest inter-metal levels correlation was observed for the Cu concentration with the Zn concentration in the gills (r = 0.87). In Subang, there was an inter-metal levels correlation involving different tissues. Here, the Cd concentration in the muscle was correlated with the Zn concentration in the digestive tract (r = 0.82). Compared to mangrove dominance sites, coastal areas of Jakarta dominated by settlements had lower pH or acidic water (Table 2). The coastal waters of Jakarta were characterized by freshwater rather than high salinity.

Heavy metal estimated daily intake in consuming P. argentata muscle

Estimated daily intake (EDI) was performed only for muscle tissue and excluded the gill and digestive tract since those excluded tissues were not consumed. Gill and digestive tracts are usually not consumed and discarded. Heavy metal EDI as a consequence of consuming *P. argentata* muscle is available in Table 3. EDI was not significant for Cd levels since the EDI value was very small if the muscle of *P. argentata* was consumed. A high EDI value for Cu was observed for *P. argentata* muscle consumption from Jakarta. A similar result was also observed for Zn. The highest EDI for Zn was also observed for *P. argentata* muscle consumption from Jakarta.

Most recent studies (Powell *et al.*, 2016) have

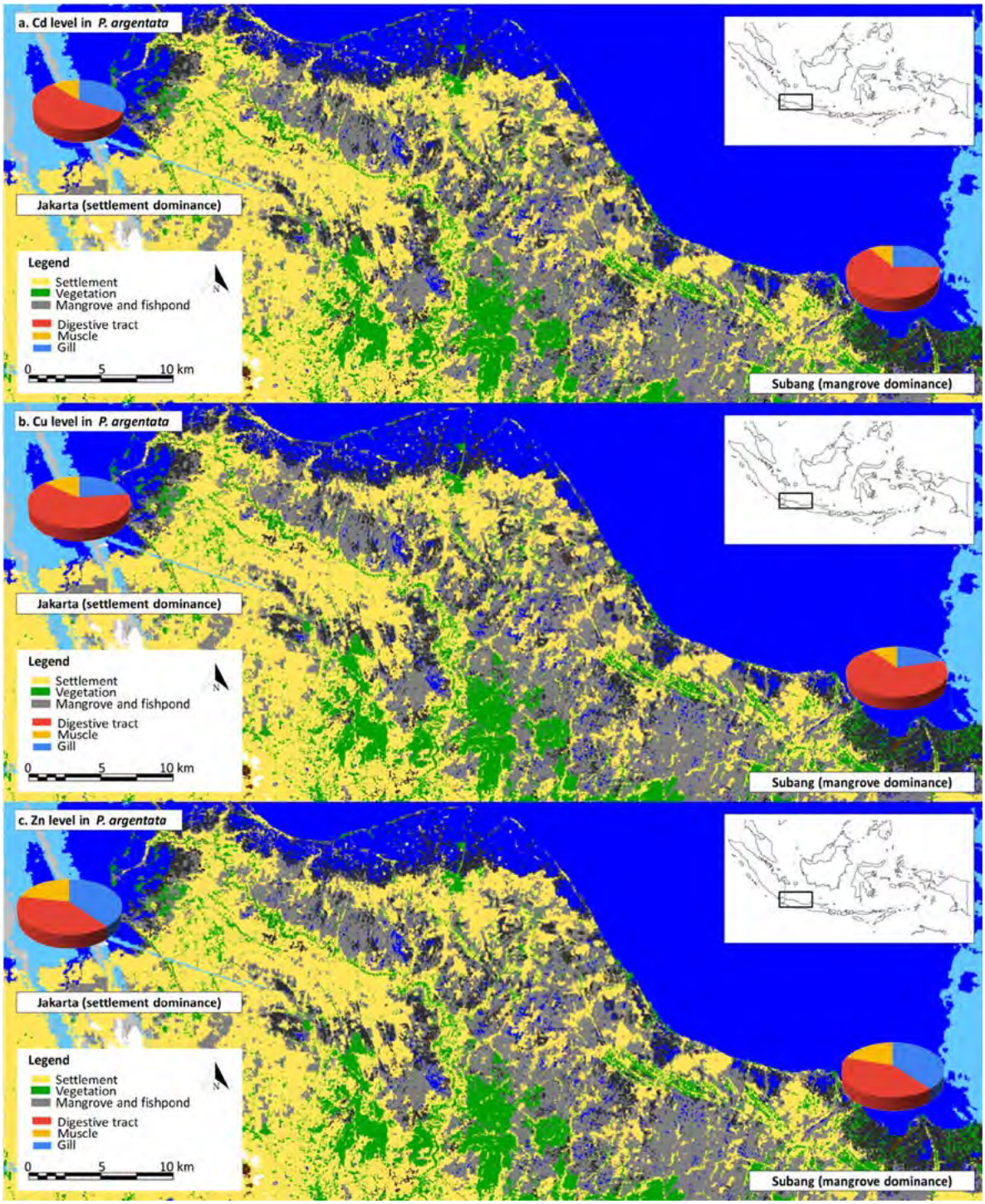

Fig. 3: Cd (a), Cu (b), and Zn (c) level compositions (pie charts) in gills, digestive tracts, and muscles of *P. argentata* related to land uses in Jakarta in the west (settlement dominance) and Subang in the east (mangrove dominance) in West Java coast, Indonesia

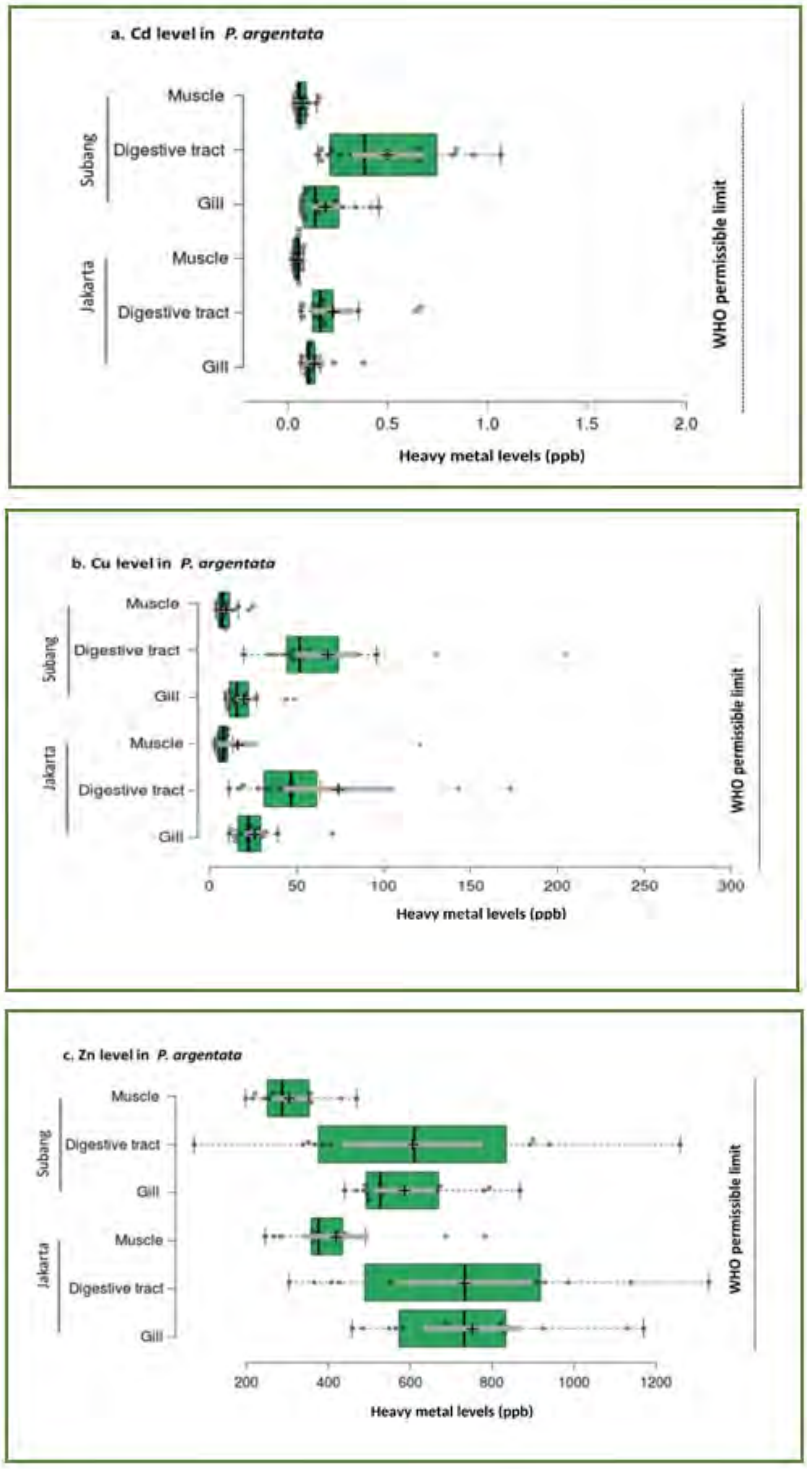

Fig. 4: Cd (a), Cu (b), and Zn (c) levels (ppb) in gills, digestive tracts, and muscle of *P. argentata* related to land use in Jakarta in the west (settlement dominance) and Subang in the east (mangrove dominance) in West Java coast, Indonesia with WHO permissible limit for Cd equals 3.0 ppb, for Cu equals 1000.0 ppb, and 100,000 ppb for Zn (Abdel-Baki *et al.,* 2011)

Table 1: Summary of the Cd, Cu, and Zn mean ± standard deviation (SD) (ppb) and ANOVA in gills, digestive tracts, and muscle *of P. argentata* related to land uses in Jakarta in the west (settlement dominance) and Subang in the east (mangrove dominance) in West Java coast, Indonesia

Heavy metals	Tissues	Mean (ppb) ± SD		Changes (%)	F	P
		Jakarta (settlement dominance)	Subang (mangrove dominance)			
Cd	Muscle	0.04 ± 0.01	0.07 ± 0.03	0.57	5.928	0.021
	Digestive tract	0.22 ± 0.18	0.50 ± 0.31	99.99	8.229	0.007
	Gill	0.13 ± 0.07	0.18 ± 0.13	41.49	1.945	0.174
Cu	Muscle	16.10 ± 29.53	9.89 ± 6.57	62.69	0.631	0.433
	Digestive tract	74.42 ± 84.33	68 ± 46.52	9.44	0.066	0.798
	Gill	25.90 ± 14.65	20.01 ± 12.08	29.42	1.441	0.239
Zn	Muscle	419.06 ± 145.36	305.46 ± 78.36	37.18	7.097	0.012
	Digestive tract	732.26 ± 297.18	606.70 ± 310.04	20.69	1.282	0.267
	Gill	751.53 ± 214.38	586.8 ± 135.11	28.07	6.338	0.017

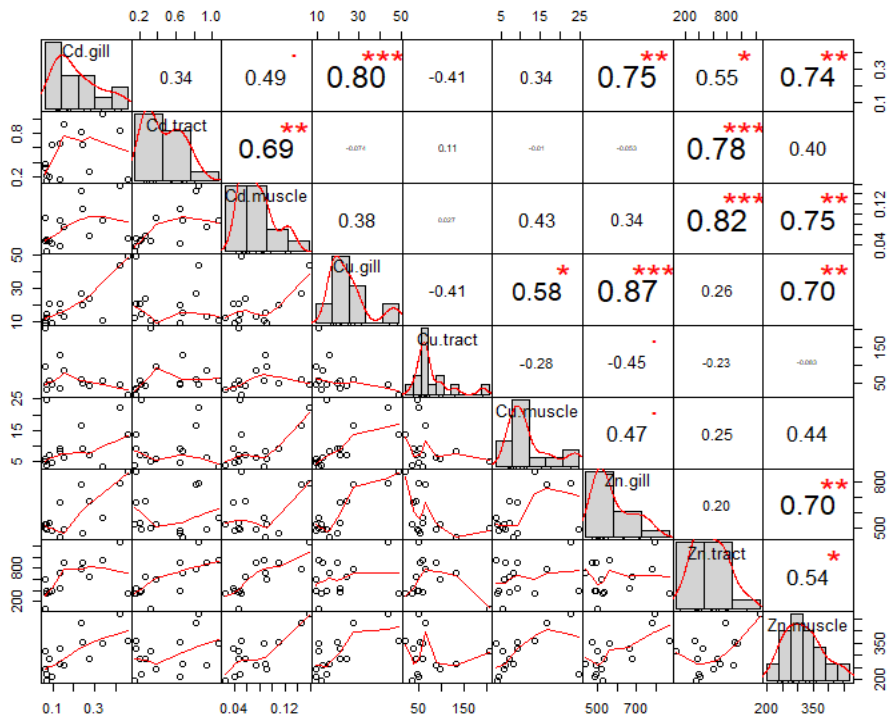

Fig. 5: Relationships between inter-metal levels (Cd, Cu, Zn) in various tissues (gill, digestive tract, muscle) in Jakarta site (***: significant at P < 0.05)

highlighted the inverse impacts of urban land use (Tóth *et al.*, 2019), mangrove cover removals (Hutchison *et al.*, 2014; Rogers and Mumby, 2019), land cover changes (Alam *et al.*, 2021), and anthropogenic disturbances on fish community and habitat degradation (Hall-Spencer and Harvey, 2019) worldwide (Lacarella *et al.*, 2018) that include as far as Antarctic Sea (Stark *et al.*, 2014), Baltic sea (Smoliński and Radtke, 2017). African continents (Britton *et al.*, 2019; Castello *et al.*, 2022), subtropical continents (Li

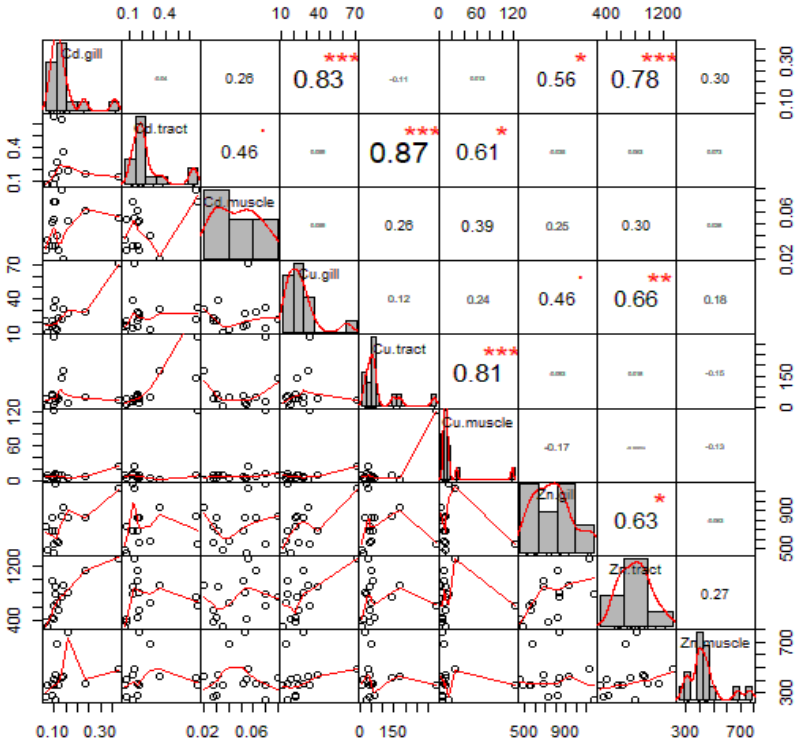

Fig. 6: Relationships between inter-metal levels (Cd, Cu, Zn) in various tissues (gill, digestive tract, muscle) in Subang site (***: significant at P < 0.05)

et al., 2018), and also tropical regions (Lo *et al*., 2020) from South America (Palacios-Sánchez *et al*., 2019; Méndez, 2021) include Brazil (Tibúrcio *et al*., 2016) to Asia. In the Asian Continent, Bella *et al.* (2021) reported impacts of land use changes in India's Western Coast, Chen *et al*. (2022) reported impacts of land use changes in Taiwan, in the China Sea (Qiao *et al*., 2022) including vast South China Sea (Rumeaida *et al.,* 2014). In particular South Asian waters (Nuon *et al.*, 2020) reported land use impacts on fish in the Mekong River basin in Sabah, Malaysia (Wilkinson *et al*., 2018), and Thailand waters Phinrub *et al*. (2014). In Indonesia, impacts of land use changes on the fish community have been reported in various areas, from Kalimantan waters (Haryono, 2020), to Banten (Mujiyanto *et al*., 2021; Sugiarti *et al*., 2021). Despite the rapidly growing research, there is still a scarcity of information on how land use changes can contribute to the magnitudes of contamination in the water that affect the fish community; here, this study has elaborated the impacts of coastal land use changes from intact mangrove to settlement in elevating the trace elements levels in fish tissues. From the results, it is obvious that trace elements in fish inhabiting Jakarta were consistently higher than trace elements contained in fish living in Subang. This indicates the differences in land uses that contribute to the transport of trace elements from land to coastal waters. Trace elements were elevated in the fish tissue due to the adsorption of heavy metals by fish accumulated in the sediments. High sediment rates in coastal waters are related to the upstream conditions. Massive conversion of vegetated areas from intact forests to settlements will increase the sediment discharge along with trace elements into the coastal waters and adsorbed by the fish. Then the levels of heavy metal in fish could be due to land-based discharges and surface run-off, which could have brought higher nutrients and chemicals to the surface waters that have become a major niche

Table 2: Summary of the physico-chemical parameters (DO, pH, salinity) mean ± standard deviation (SD) in Jakarta in the west (settlement dominance) and Subang in the east (mangrove dominance) on the West Java coast Indonesia

Physico-chemical parameters	Mean ± SD		F	P
	Jakarta (settlement dominance)	Subang (mangrove dominance)		
DO	19 ± 1.47	6.32 ± 0.12	220.516	0.000
pH	6.98 ± 0.20	7.7 ± 0.1	29.337	0.005
Salinity	24 ± 10.14	35.5 ± 0.00	3.851	0.121

Table 3: Summary of estimated *P. argentata* muscle daily intake (µg/kg/day) for Cd, Cu, and Zn related to land uses in Jakarta in the west (settlement dominance) and Subang in the east (mangrove dominance) in West Java coast, Indonesia

Heavy metals	Person	Estimated *P. argentata* muscle daily intake (µg/kg/day)	
		Jakarta (settlement dominance)	Subang (mangrove dominance)
Cd	Children	<0.01	<0.01
	Adult	<0.01	<0.01
Cu	Children	0.02	0.01
	Adult	0.03	0.02
Zn	Children	0.64	0.46
	Adult	0.69	0.50

Table 4: Summary of recent literature on heavy metals in *Pennahia*

Heavy metals	Tissue	Value	Location	References
Cu	Muscle	1.33 ± 0.01	Kapar coast, Malaysia	Bashir *et al.*, 2015
	Gills	2.89 ± 0.03		
Cd	Muscle	0.03 ± 0.01		
	Gills	0.16 ± 0.01		
Zn	Muscle	20.62 ± 1.3		
	Gills	115.7 ± 5.5		
Cd	Muscle	0.02 ± 0.3	Mersing coast, Malaysia	Fathi, 2014
	Gills	0.05 ± 0.01		
Zn	Muscle	18.1 ± 0.79		
	Gills	66.24 ± 1.30		

habitat for fish (Yap and Al-Mutairi, 2022). *Pennahia argentata* is a benthopelagic species preferring muddy bottom. Its microhabitat explains that this fish is prone to trace elements usually accumulated in the sediments. Benthic fish are thought to have higher heavy metal concentrations than fish in the upper water column because they are in direct touch with the sediments and take in more heavy metal concentrations from zoobenthic predators. The order of trace elements in fish muscle in both sites was Zn > Cu > Cd. This trace element order is compared to the previous study (Table 4) in comparable South East Asian coasts. According to Takarina *et al*. (2021), Zn is a common trace element recorded in commercial fish on the West Java coast. In both sites, digestive tracts are the tissues that always consistently have higher heavy metal levels compared to other tissues. Heavy metals observed in digestive tracts range from titanium (Ti), vanadium (V), Cr, manganese (Mn), Fe, cobalt (Co), nickel (Ni), Cu, Zn, As, selenium (Se), bromine (Br), strontium (Sr) and Pb (Dane and Şisman, 2019). In this study, Cd, Cu, and Zn were detected in this tissue. Heavy metal levels in digestive tracts can have inverse effects on the health status of the fish species. These effects ranged from intestine swelling, infiltration, vacuolization, gastric degenerations, epithelial degenerations, fibrosis, congestion, fusion, and hyperplasia, which were more common in fish species inhabiting polluted sites influenced by anthropogenic activities. Gill is the second tissue with

high heavy metal levels for all trace elements in both sites. According to Gu *et al*. (2017), heavy metal tends to be higher in gills than in other tissues. The principal site for heavy metal uptake is in the gills, which are the first target of waterborne pollutants and are extremely susceptible to heavy metal buildup because of constant exposure to the outside environment. Heavy metal accumulation in gill tissues is caused by heavy metal absorption through the gill surface, which is sometimes difficult to remove. The maximum buildup of heavy metals occurs due to the gill tissues' extremely branched form and water movement through them (Shah *et al*., 2020). Gills are the main mechanism for metal ion exchange from water, as their vast surface surfaces allow for the fast diffusion of hazardous metals. As a result, metals deposited in gills are thought to be primarily concentrated in water. Muscle is the only tissue in both sites that consistently has the lowest heavy metal levels for all trace elements. This discovery is supported by earlier research. According to Al-Najjar *et al*. (2016), trace elements found in muscle were consistently lower than heavy metal levels found in other tissues. *P. argentata* is a carnivore that feeds on small fish and invertebrates (Huh *et al*., 2018). The level of trace elements is connected to the feeding habits of the fish. Metal concentrations in fish muscles are often higher in herbivore fish than in carnivore fish (El-Moselhya *et al*., 2014). This explains the low amounts of heavy metals in *P. argentata* muscle, considering that *P. argentata* is carnivore fish (Koh *et al*., 2014). Heavy metal uptakes in fish were also related to the physicochemical parameters of water. Heavy metals in fish in settlement dominance sites were high, and at the same time, these sites were characterized by lower pH or acidic water. According to Jezierska and Witeska (2006), water acidification causes metal bioaccumulation in fish via modifying the solubility of metal compounds or directly by causing damage to the epithelia, which becomes more permeable to metals. On the other hand, the competitive uptake of H^+ ions may impede metal absorption. Besides that, the bioavailability of heavy metals was higher in waters with lower pH (Moiseenko and Gashkina, 2020).

According to this study, Cd has the lowest EDI and may pose the least risk to the community if consumed. Low EDI for Cd in fish is also reported by Djedjibegovic *et al.* (2020). High EDI was observed only for Cu and Zn in Jakarta. Because the EDI for Zn in Jakarta is high, consuming fish muscle should be done with caution. Zn, a trace element, is a common trace element that increases the risk of seafood consumption worldwide (Korkmaz *et al*., 2019). Due to consuming fish containing heavy metals, possible health risks and diseases include the risk of cancer developing over time with exposure to the chemicals at low doses (Bassey and Chukwu, 2019). Because this study confirms that heavy metal presences are linked to land use changes in coastal areas, it is strongly advised that coastal development be regulated. The conversion of intact mangrove forests to fishponds and settlements must be stopped. Besides that, it is also recommended to develop versatile bioindicators by choosing a fish species.

CONCLUSIONS

Most studies on heavy metal levels in coastal fish ignore the source and origin of heavy metals, a feature of land use. Land use changes are affected by anthropogenic activities such as agriculture, urbanization, and deforestation. This study is the first of its kind successfully describe and link the effects of different land uses on trace elements in commercial fish. In conclusion, Cu and Zn in muscle fish living along the coast near settlements were 62.69% and 37.18% higher ($P < 0.05$) than Cu and Zn in fish living on mangrove coasts. This explains the variations in land use for increasing levels of heavy metals in fish. In addition, the largest amount of Cd and Cu is found in the digestive tract, with a value of 0.22 ppb and 74.42 ppb. Meanwhile, the highest level of Zn is found in gill, with a value of 751.53 ppb in Jakarta, a densely populated coastal settlement. These results confirmed that the digestive tract consistently had the highest levels of trace elements, followed by gills and muscles, respectively. The research results prove that the digestive tract can be selected as a particular fish tissue to be used as a bioindicator for monitoring Cd, Cu, and Zn, especially on the coast of West Java, Indonesia. Based on heavy metal content and EDI calculations, Jakarta has the highest trace elements in fish. Differences in land use cause an increase in sediment discharge along the coastal waters. Zn and Cu have a greater daily intake rate than Cd at the two sampling locations. Zn metal has a very significant EDI for children and adults of 0.64 and 0.69 on the coast of Jakarta. Therefore, the consumption of fish

muscle must be done with caution at the risk of considering the high Zn content, especially in Jakarta, which has the highest land use changes between the two sampling locations. As a novelty, this research has linked the associations between land use, the magnitudes of heavy metals in fish, and the potential health risks of consuming these contaminated fish. This identification of associations has made a significant contribution to environmental sciences, particularly concerning pollution management and heavy metal monitoring.

AUTHOR CONTRIBUTIONS

ND. Takarina, as the corresponding author, has contributed to funding, contributing to the proposal, and drafting the manuscript; O.M. Chuan conducted in preparation of the manuscript, reviewing proposals and data verification; T.G. Pin is the field coordinator, conducted fish sampling and helped in creating maps. I. Femnisya performed laboratory analysis for Subang fish samples and data tabulation. A. Fathinah contributed to laboratory analysis for Jakarta fish samples and data tabulation. A.N.B. Ramadhan did the Subang sample preparation and administered technical support. R. Hermawan did the Jakarta samples preparation and data tabulation. A. Adiwibowo drafted the manuscript, data analysis, and data interpretation.

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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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ABBREVIATIONS

°	Degree
%	Percentage
am	Ante meridiem
ANOVA	Analysis of variance
As	Arsenic
Br	Bromine
°C	Celsius degree
Cd	Cadmium
CI	Confidence interval
Co	Cobalt
cm	centimeter
Cr	Cromium
CRMs	Certified reference materials
Cu	Copper
DO	Dissolved oxygen
EDI	Estimated daily intake
EL	East longitude
F	Means between population/ distribution
Fe	Ferro
g	Gram
g/day	Gram per day

GIS	Geographical Information System
GPS	Global positioning system
HCl	Hydrochloric acid
H'	Shannon-Wiener index
HNO_3	Nitric acid
ICP	Inductively coupled plasma
kg/km^2	Kilogram per square kilometer
mL	Milliliter
mg/kg	Miligram per kilogram
Mn	Manganese
N	North
na	Not available
NE	Not evaluated
Ni	Nickel
P	Probability / significant value
Pb	Lead
ppb	Part per billions
pH	potential of hydrogen
pm	Post meridiem
r	Pearson correlation value
SD	Standard deviation
Se	Selenium
SL	South latitude
Sr	Strontium
Ti	Titanium
V	Vanadium
WHO	World Health Organization
µg/g	Microgram per gram
µg/kg/day	Microgram per kilogram
x^2	Chi square
Zn	Zinc

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ORIGINAL RESEARCH PAPER

Spatial delineation on marine environmental characteristics using fuzzy c-means clustering method

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ABSTRACT

BACKGROUND AND OBJECTIVES: Conservation efforts are often prioritized on a large spatial scale because information about local ecosystems is frequently lacking. Therefore, comprehensive spatial classification of a region's environmental characteristics is essential for effective marine conservation. This study aimed to construct geophysical and chemical environmental delineation of the Lesser Sunda Islands which are located in Indonesia. This area is an ecoregion in the coral triangle that has been a primary concern of global biodiversity conservation strategies.

METHODS: This study utilized eleven global environmental variables that were accessed from global marine databases. After performing a principal component analysis, a fuzzy C-means clustering technique was used to classify the region into groups based on environmental characteristics in term of seasonal variability. It was expected that the areas within each group would have identical attributes and ecological processes.

FINDINGS: The results suggested that the marine environmental factors in Lesser Sunda can be simplified using a principal component analysis technique: 6 principal component factors explained 81.06 percent of the overall raw data variability for the wet season, and 7 principal component variables explained 84.51 percent of the overall raw data variability for the dry season. Then, the area can be delineated into 5 groups (wet season) and 10 groups (dry season) with different environmental characteristics. This method's classified groups principally inferred the Indian Ocean and Bali Sea, Savu Sea and Flores Sea, and Banda Sea as distinct clusters. In particular, the group that included the Indian Ocean had characteristics including lower nitrate and sea surface temperature concentrations, as well as higher potential hydrogen salinity and distance from the shore.

CONCLUSION: The findings of this study showed that the single marine conservation area in Lesser Sunda is not sufficient to adequately represent the physicochemical dynamics in the area. The proposed delineation result will supplement the existing bioregion classification of marine areas, such as the Marine Ecoregions of the World. Moreover, it is also consistent with existing conservation programs, including the notable national marine protected areas of the Savu Sea. Nevertheless, the acknowledged biogeographic group of the Indian Ocean indicates that countries must work together to successfully manage marine protected areas and achieve their conservation objectives. This work serves as a baseline for both academic research and ecological assessment, and it will contribute to marine protected areas strategies and conservation efforts in the Lesser Sunda Islands.

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47	6	2

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INTRODUCTION

In recent years, the marine environment, including its bio-physical and ecological functioning, has been facing potentially significant threats. Climate change is perceived as a major factor that contributes to the degradation of marine ecosystems and negatively impacts their perseverance, functionality, and related ecosystem services (Doney *et al.*, 2011; Smale *et al.*, 2019). Examples of climate change-induced stressors for ocean life include increased sea surface temperatures (SST), acidification, changing patterns of currents and productivity, a rise in sea levels, and decreased dissolved oxygen (IPCC, 2013). Heavy rainfall during the wet season can cause an influx of fresh water into the ocean, which alters salinity levels and disrupts the delicate balance of the environment. Some species' reproduction and survival may suffer as a result. Furthermore, an increase in precipitation can cause increased runoff, which can carry pollutants and excess nutrients into the water, causing problems like eutrophication and algal blooms (Ullah *et al.*, 2021). During the dry season, however, there may be less rainfall, resulting in decreased water levels in rivers and streams that drain into the ocean. This can also cause ecosystem disruption and changes in the distribution and behavior of some species (Doney *et al.*, 2011). Conservation of this environment is essential for preserving the earth's natural systems; it mitigates climate change, promotes adaptation, and ensures socioeconomic benefit (Marcos *et al.*, 2021). Currently, marine protected areas (MPAs) have emerged as a crucial component of efforts to conserve marine biodiversity. MPAs help to impede or lessen the effects of stressors (Sullivan-Stack *et al.*, 2022). MPAs are a type of area-based conservation strategy that are widely used to protect marine ecosystem services and biodiversity (Sullivan-Stack *et al.*, 2022). They are zones in which human activity is limited in order to properly manage and preserve marine and coastal resources from various threats, such as overfishing and habitat destruction. MPAs are widespread throughout the world, and research has shown that they preserve ecosystem services, halt the downturn of threatened ecosystems, and restore food systems (Gallacher *et al.*, 2016). To better plan marine conservation strategies, it is crucial to gain a comprehensive understanding of oceanographic processes and of the distribution of marine species (Lourie and Vincent, 2004). The Coral Triangle (CT) is a marine conservation area in the Western Pacific and parts of South-East Asia. Its sea area is larger than that of the Atlantic and Mediterranean combined in Europe (Asaad *et al.*, 2018; Linggi and Burhanuddin, 2019). Several initiatives have been launched to conserve this region's high levels of marine diversity (Estradivari *et al.*, 2022). The CT has been divided into a number of ecoregions, one of which is the Lesser Sunda region (Setyawan *et al.*, 2018). These areas are situated at a "crossroads" of major global climate forces, making them the most hostile tropical habitat in the Indonesian sea region (Mahrup *et al.*, 2021). The marine waters of the islands of Lesser Sunda form the habitats of 2631 reef fish species and 76 percent of coral reef species. The islands are also home to sea turtles and several marine mammal species such as the dugong and various species of dolphins and whales. Ultimately, the Lesser Sunda Islands are a significant biodiversity hotspot, and efforts are still being made to preserve the rare marine species that live there (Setyawan *et al,* 2018). However, the region has become increasingly affected by the environmental repercussions of human activities (Perdanahardja and Lionata, 2017). Physical and biological environments shape the structure and functioning of marine systems, act as surrogates for species and habitat distribution (data for which are hard to acquire at large scales), and aid in conservation planning. Conservation efforts are prioritized at a large spatial level because information about local ecosystems is frequently lacking (Wang *et al.*, 2015). These physical and biological environments must be classified using remote sensing techniques to gain a thorough knowledge of the area of interest, determine priority sites for quick assessments or monitoring, and construct ecologically representative MPA systems that integrate each habitat type in each of the environments (Chollett *et al.*, 2012). Therefore, a comprehensive spatial classification of the region's environmental characteristics is required to assist plans for marine conservation in the Lesser Sunda Island area. This goal can be met by employing the unsupervised classification method; the primary goal of this method is to generate classification identifiers instantaneously. Unsupervised methods look for similarities between data points to seeing if they can be classified by forming groups known as clusters. Unsupervised methods are commonly used in remote sensing include K-means, Fuzzy C-means (FCM), and neural network-based methods. FCM

outperforms K-means when the data set cannot be clearly subdivided into underlying partitions (Perez-Ortega *et al.,* 2022). Previous research has attempted to delineate the biophysical conditions of the Lesser Sunda Islands by using the Self-Organizing Map (SOM) neural network approach (Wang *et al.*, 2015). However, the FCM clustering technique has been shown to perform better (Mingoti and Lima, 2006). As a result, in the sense of marine environments, FCM could be used to categorize various types of marine habitats based on a variety of input variables like water temperature, salinity, and dissolved oxygen levels. Such variables can be retrieved from remote sensing databases, resulting in a large amount of data that may impede the execution of FCM's algorithm (Lasram *et al.*, 2015). As a result, to improve the performance of FCM, principal component analysis (PCA) can be used to adequately reflect variable differences and improve algorithm speed (Sârbu and Pop, 2005). Therefore, the present study aims to divide the Lesser Sunda Island area into clusters based on globally accessible remote-sensing satellite environmental characteristics using FCM and PCA. This is to supply conservation efforts on a smaller spatial scale in the Lesser Sunda Islands, which is unavailable. The study will aid in the identification of conservation priorities. This study has been performed in the Lesser Sunda Islands of Indonesia in 2023.

MATERIALS AND METHODS

Study area

The Lesser Sunda Islands are located in Indonesia and divided into four administrative provinces, which include Bali, West Nusa Tenggara, East Nusa Tenggara, and Maluku, as well as territories within Timor Leste (Fig. 1). The area included information of marine species which were mostly from the families Labridae (122 species), Gobiidae (102 species), and Pomacentridae (85 species). This means that, among marine species, the Lesser Sunda Islands were dominated by the reef fish family. This is a logical conclusion, because the Lesser Sunda Islands area is a key region of marine biodiversity that is situated in the center of the Coral Triangle (Setyawan *et al.*, 2018).

Data collection

The environmental variables used in this study were selected according to their relevance to marine species distribution and based on knowledge from previous

Fig. 1: Geographical location of study area in the Lesser Sunda Islands, Indonesia

studies. The details of each variable are presented in Table 1. These environmental data were obtained from the Marine Spatial Ecology (MARSPEC) and Bio-Oracle databases. This global database provides current, satellite-based information about the oceanic surface and seabed at a spatial resolution of 30 arc seconds (~ 1 km^2) (Sbrocco and Barber, 2013). The environmental data are divided in terms of the seasonal patterns (dry season and wet season) of the study area.

FCM clustering method

Clustering is a method that divides a given set of unidentified data into a series of clusters. Data in each cluster are highly similar, with distinct differences in characteristics among clusters. A clustering approach that includes the minimization of some objective function corresponds to the group's objective function algorithms. When an algorithm can minimize an error function, it is referred to as C-means. It is known as FCM if the number of classes or clusters utilized is c, and if the relevant classes utilize the fuzzy approach or simply fuzzy (Mingoti and Lima, 2006). The FCM method employs a fuzzy membership that assigns a degree of membership to each class. The importance of degree of membership in fuzzy clustering is analogous to the pixel probability assumption in mixture modeling. FCM has the advantage of forming new clusters from data points with similar membership values to current classes. The fuzzy membership function, partition matrix, and objective function are the three basic operators in the FCM approach (Deng, 2020). Table 2 describes various applications of the FCM clustering technique.

The FCM technique is the most extensively used and is one of the most effective fuzzy clustering algorithms (Deng, 2020). Based on the assumption that a set of data $D=\{x_i\}_{i=1}^{n}$ and k denotes the number of clusters, the objective function of FCM can be defined using Eqs. 1 and 2 (Deng, 2020).

$$J_m(U,C)=\sum_{i=1}^{n}\sum_{j=1}^{k}\mu_{ij}^{m}x_j-c_j^{\,2} \tag{1}$$

Restricted with

$$\sum_{j=1}^{k}u_{ij}=1,\forall i \tag{2}$$

Where;

$D=\{x_i\}_{i=1}^{n}$ = dataset with a size of n

$U=\{\mu_{ij}\}_{i,j=1}^{n,k}$ = membership matrix

$C=\{c_j\}_{j=1}^{k}$ = centroids of each cluster

k = number of clusters

The Frobenius norm ‖*‖ is utilized to compute the differences between matrices. In addition, the fuzziness of the clustering algorithm is determined by the fuzzy coefficient $m\in[1,\infty)$. A higher m value results in more difficult clustering, with each data point strongly associated with a single cluster. A value m closer to infinity results in smoother clustering, with each data point belonging to multiple clusters to varying degrees. This can affect the accuracy of spatial delineation of marine environments because it determines how well the algorithm can distinguish between different types of habitats or regions (Perez-Ortega *et al.,* 2022). A higher level of fuzziness may result in habitats being

Table 1: Environmental variables used in the study

No.	Variable	Unit
1	Sea surface chlorophyll (SSC)	mg/m^3
2	SST	^{0}C
3	nitrate	µmol/m^3
4	salinity	PSS
5	Potential of hydrogen (pH)	-
6	depth	m
7	slope of the seabed	degree
8	distance to shore	km
9	current velocity	m/s
10	the eastness (aspect EW) of the slope	radians
11	the northness (aspect NS) of the slope.	radians

Table 2: Environmental variables used in the study

No.	Application	References
1	Water quality of Danube lake	Sârbu and Pop (2005)
2	Image processing	Lázaro *et al.* (2005)
3	The case of forest fires	Iliadis *et al.* (2010)
4	Optimization in Computer Forensics	Wang *et al.* (2012)
5	Modeling of beta diversity in Tunisian waters	Lasram *et al.* (2015)
6	Key performance indicator in business	Tokat *et al.* (2022)
	Hospital clustering	Setiawan *et al.* (2023)

grouped together that are actually distinct, while a lower level of fuzziness may result in habitats being separated that are actually similar. Therefore, the choice of membership degree as well as the number of the cluster (k) should be determined by using reliable criteria such as the Silhouette index. Optimal clustering results can be obtained by establishing the Lagrange equation, as shown in Eq. 3, for Eq. 1, under the restriction provided in Eq. 2 (Deng, 2020).

$$J_m(U,C)=\sum_{i=1}^{N}\sum_{j=1}^{K}\mu_{ij}^m x_j - c_j^{\,2} + \lambda\left(u_{ij}-1\right) \quad (3)$$

The partial derivative of Eq. 3 yields the membership equation, as shown in Eq. 4, as well as the centroid, as shown in Eq. 5 (Deng, 2020).

$$u_{ij}=\frac{1}{\sum_{k=1}^{c}\left(\frac{x_i-c_j}{x_i-c_k}\right)^{\frac{2}{m-1}}} \quad (4)$$

$$c_j=\frac{\sum_{i=1}^{n}\mu_{ij}^m x_i}{\sum_{i=1}^{n}\mu_{ij}^m} \quad (5)$$

The FCM algorithm can be presented as follows (Jaffar *et al.*, 2009):

Input dataset D and k

Output U and C *Process*

1. Randomly initialized U
2. Repeat 3 and 4 until $C_t - C_{t-1} < \varepsilon$
3. Compute c_j
4. Compute u_{ij}

Principal component analysis (PCA)

PCA is a class of multivariate analysis, which transforms the original set of the study variables into its principal components. In general, it is used to reduce the dimensionality of the variables of interest (Lusiana *et al.*, 2022). Because this analysis uses a large volume of data, the sampling adequacy criteria were tested by using the Kaiser-Meyer-Olkin (KMO) test (KMO > 0.50). Furthermore, a significant Bartlett test ($p < 0.05$) was also required to be fulfilled to support data homogeneity (Gañan-Cardenas and Correa-Morales, 2021).

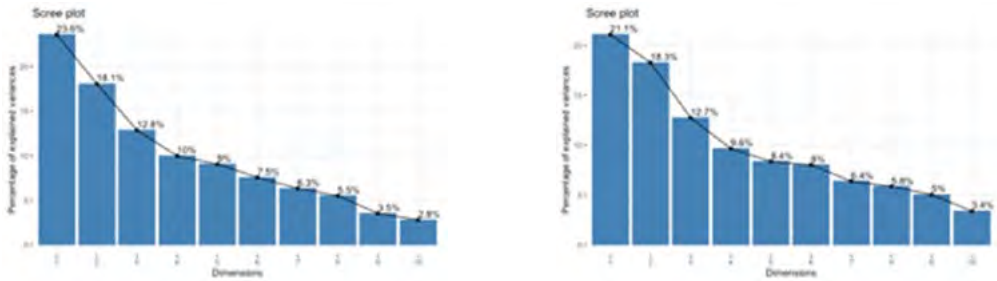
RESULTS AND DISCUSSION

PCA results

The prerequisite analyses for PCA, such as the KMO and Bartlett tests, showed that the data size of this study was adequate for both seasons (KMO > 0.50) and homogenous ($p < 0.05$). The cumulative data showed that the variance of the six principal components of the wet season was 81.06 percent (Fig. 2a), while the seven principal components of the dry season accounted for 84.51 percent (Fig. 2b). These principal components are sufficient to represent the complex original data as the input for further analysis on environmental data layers (Fitzpatrick *et al.*, 2013).

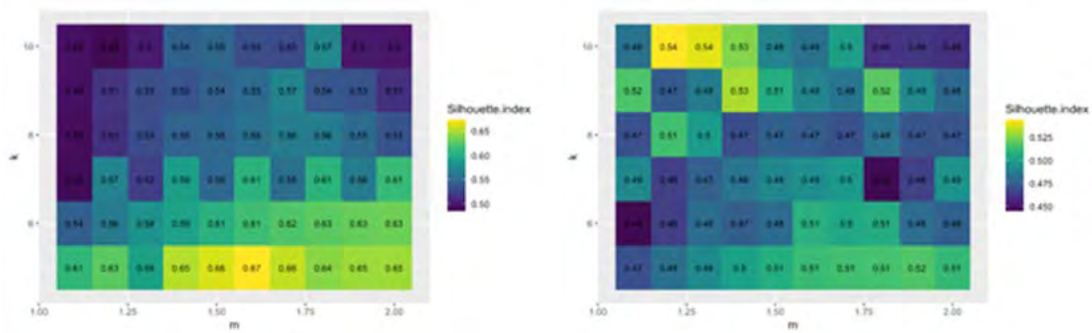
Spatial delineation groups

The analysis of FCM for spatial delineation started with by identifying the optimum number of clusters (k) and the fuzzy coefficient (based on the Silhouette index criterion for each season. As shown in Fig. 3a, the best clustering results for the wet season were achieved at $k=5$ and $m=1.6$. On the other hand, for the dry season, the optimum clusters were obtained with $k=10$ clusters and a fuzzy coefficient of $m=1.2$ (Fig. 3b). These results implied that the number of clusters is inversely proportional to the fuzzy coefficient value. As a result, the spatial delineation results during the wet and dry season are largely different, whereas the number of clusters formed in the dry season was double that of the wet season. This means that the environmental characteristics of the dry season are more variable than those of the wet season.



(a) (b)

Fig. 2: Scree plot of PCA result (a) wet season; (b) dry season

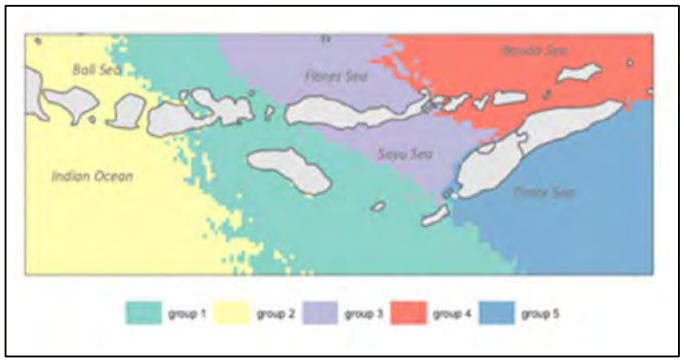


(a) (b)

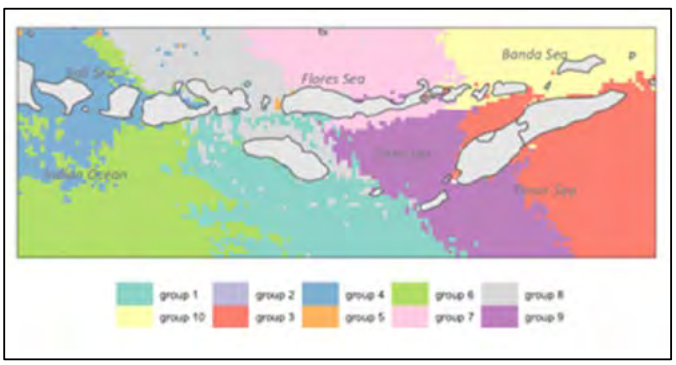
Fig. 3: Silhouette index plot of FCM (a) wet season; (b) dry season

FCM clustering of environmental characteristics in the Lesser Sunda Islands resulted in five groups. For the wet season (Fig. 4a), Groups 1 and 3 primarily cover the Savu Sea and Flores Sea. Group 2 represents the Bali Sea and Indian Ocean, while Group 4 denotes the Banda Sea. Finally, the Timor Sea is covered by Group 5. Meanwhile, a more diverse delineation or groups was obtained in the dry season, which resulted in 10 groups (Fig. 4b). Compared to the wet season, Group 1 in the wet season splits into Groups 4 and 6 in dry season, while Group 2 (wet season) becomes Groups 1 and 8. Meanwhile, Groups 3, 4, 5 in the wet season correspond with Groups 3, 7, 9, and 10 in the dry season. The dry season in Indonesia's Lesser Sunda Islands brings more steady weather and less rainfall, which could result in more distinct marine environmental features. There is commonly more cloud cover and precipitation during the wet seasons, which can heavily impact visibility and temperature, as well as the distribution and behavioral patterns of marine organisms (Ullah *et al.*, 2021). Furthermore, during the dry season, human activities such as fishing and tourism may increase, which could further shift marine environmental attributes (Lincoln *et al.*, 2022). Specifically, during the wet season from November–January, many cetacean animals were found in areas of the Lesser Sunda Islands such as the Savu Sea and Flores Sea. It includes migratory bottlenecks for endangered whale species—such as sperm and blue whales—that are of regional conservation importance (Perdanahardja *et al.*, 2017).

Conservation efforts must include a complete sense of the scale at which they engage and the scale at which their objectives (biological units) act. Conservation priorities are frequently set at large geographic scales, but their execution occurs at small scales (Costanza *et al.*, 1998). Broader scales of analysis may highlight important characteristics worldwide while overlooking significant regional ones, even if they may assist the globally significant ones (e.g., to benefit turtles, both feeding and nesting sites should be safeguarded). Linking conservation initiatives at the local, regional,



(a)



(b)

Fig. 4: Spatial delineation results of FCM clustering on the Lesser Sunda Islands (a) wet season; (b) dry season

and global scales would promote partnerships and collaboration (Mace *et al.*, 2000). Research on the geographical distribution functions of organisms, known as biogeography, could potentially play a major role in systematic marine conservation programs (Lourie and Vincent, 2004). Systematic planning entails a comprehensive view of the entire system, which includes defining conservation goals, gathering data, setting objectives, evaluating the contribution of existing areas to achieving goals, compiling a portfolio of regions for consideration, and defining focus areas for conservation action (Groves *et al.*, 2002). Marine conservationists have long recognized the need for holistic and detailed research on marine biogeography at a global scale. In recent years, the urgency of this need has increased due to the necessary approaches required for the designation of marine protected areas in various national, regional, and international planning agreements and legal frameworks (Costello and Chaudhary, 2017). The results obtained by spatially delineating the Lesser Sunda Islands in this study supplement the existing bioregion classification of marine areas, such as the Marine Ecoregions of the World (MEOW). MEOW is a classification of global coasts and shelves based on biogeography and was designed to be closely linked to existing regional systems. Ecoregions are subdivided into the larger biogeographic strata of realms and regions (Spalding *et al.*, 2007). According to MEOW, the area of the Lesser Sunda Islands (i.e., 30131) was solely classified as the Lesser Sunda Seascape (Spalding *et al.*, 2007).

Characteristics of spatial delineation groups

The study findings revealed different environmental characteristics throughout the study area during the wet season (Fig. 5) and the dry season (Fig. 6). In comparison to the other groups, groups that represent the Indian Ocean had the highest pH, salinity, and distance to shore, as well as lower nitrates and SST. This suggests that a single marine conservation area in the Lesser Sunda Islands is not sufficient to adequately represent the physicochemical dynamics in the area, which affect the distribution and diversity of marine species.

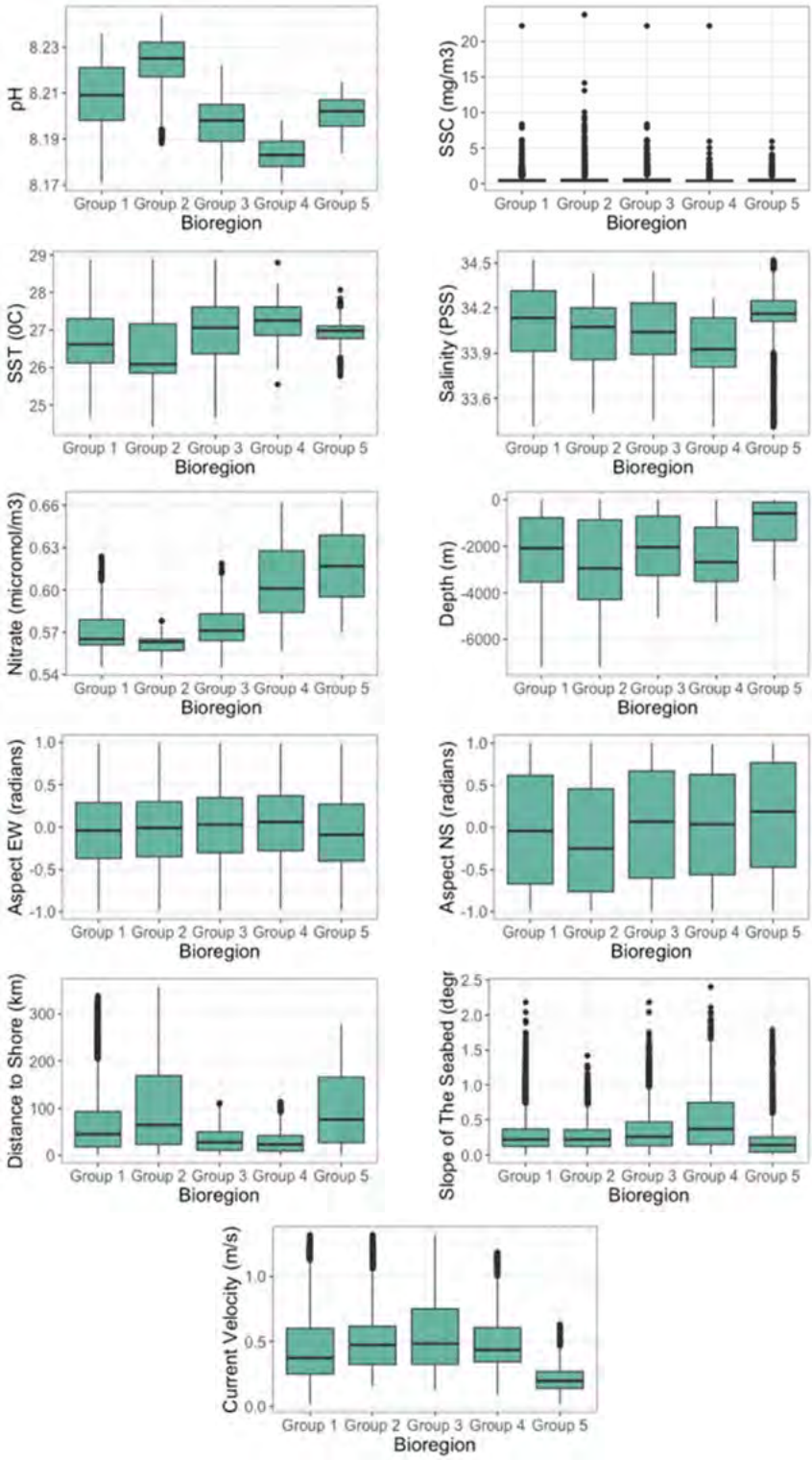


Fig. 5: Environmental characteristics of each FCM delineation group in the wet season

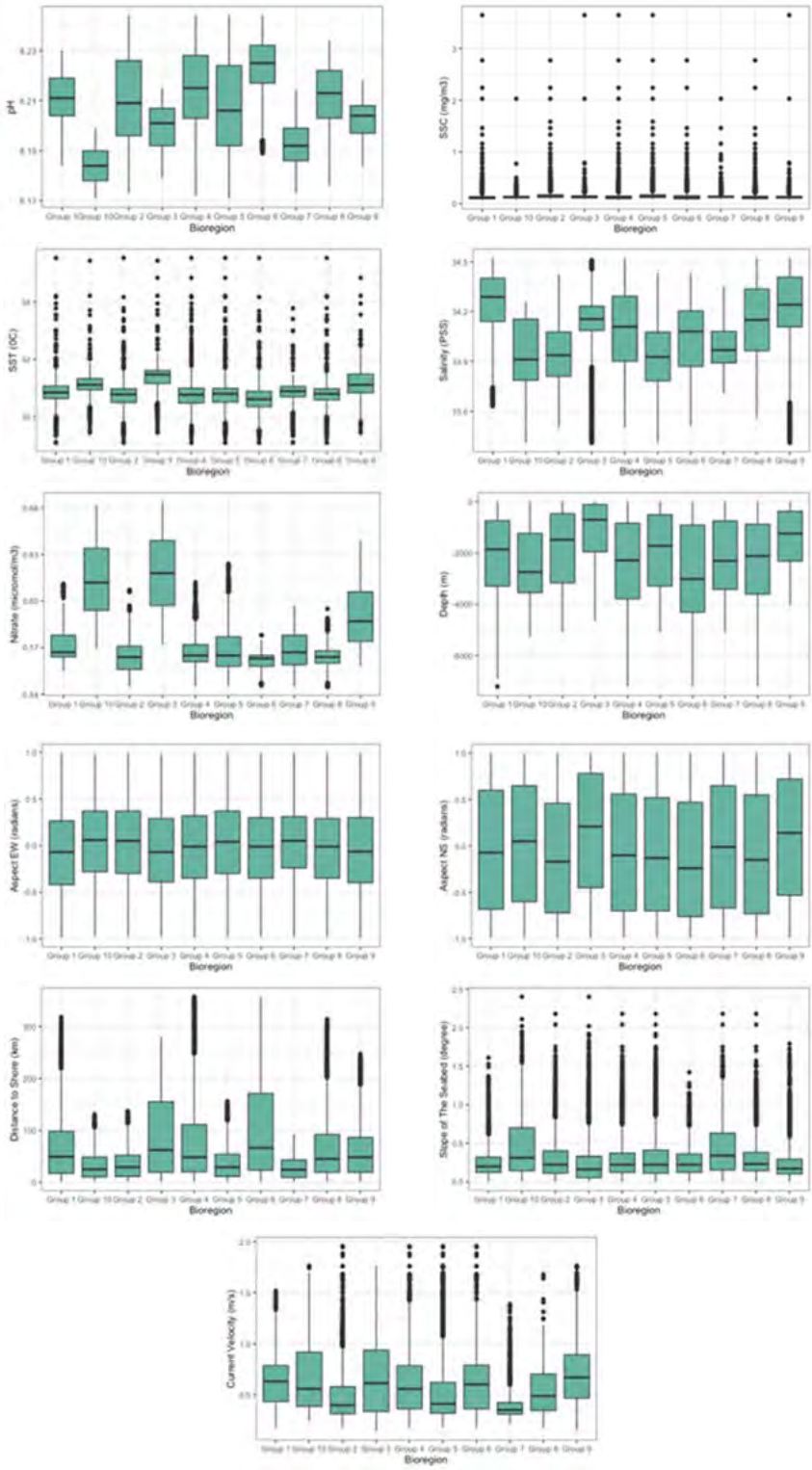


Fig. 6: Environmental characteristics of each FCM delineation group in the dry season

It is evident that the physicochemical conditions in Group 1 are affected by two main natural phenomena, namely, the Indian Ocean Dipole (IOD) and the El Nino-Southern Oscillation (ENSO). The Indian Ocean experiences significant interannual changes as a result of the frequent co-occurrence of these events (Sprintall and Révelard, 2014; Zhang *et al.*, 2022). Low-salinity tropical waters are transported from the Pacific to the Indian Ocean by way of the Indonesian Ocean via the Indonesian Throughflow (ITF). The ITF links ocean basins and is the only tropical oceanic route; therefore, it is crucial to sea circulation and to the earth's climate. Its interannual variability is primarily determined by ENSO-related air current forcing via the Pacific waveguide. However, the IOD may shift the impact of the Pacific ENSO via the wind fluctuation in the Indian Ocean, as well as the Indian Ocean waveguide (Sprintall and Révelard, 2014). Since the Indian Ocean is bounded by numerous countries, its various MPAs are managed individually. Research suggests that cooperation between these countries is essential to achieve the effective conservation of ecological systems and organisms across the islands and continental countries in the region (Levin *et al.*, 2018). Some ways that countries can coordinate to conserve marine ecosystems include regional cooperation through regional organizations, such as the United Nations Convention on the Law of the Sea (UNCLOS) or the Convention on Biological Diversity (CBD), to establish shared conservation goals and coordinate conservation efforts (Wartini, 2022). Moreover, countries can establish transboundary marine protected areas that span multiple countries and provide coordinated conservation efforts for the shared marine resources as well as collaborate on research and monitoring of marine ecosystems to improve understanding of shared resources and the impact of human activities (Gómez-Ballesteros *et al.*, 2021). In this study, the groups that covered the Savu Sea are characterized by high levels of nitrate and SST, low pH, and mild salinity. Further, the ITF that moves into the Savu Sea via the Ombai Strait contributes to a physical environment that both sustains sea life and supplies resources for the community. Due to its unique oceanographic features, such as deep trenches, oceanic currents, and upwelling areas, the Savu Sea is an important shelter and migratory pathway for cetaceans and turtles, a vital nursery ground, and an ideal location for coral reefs (Mujiyanto *et al.*, 2017). As a result, it contains extraordinary biodiversity and an abundance of marine species, particularly mammals (Mustika, 2006). It has incredibly diverse coral reefs that act as an essential ecosystem for a variety of marine organisms. Moreover, it is a fishing spot that acts as a major economic resource for coastal communities (Mustika, 2006). Finally, the finding in this study recommends that the conservation planning of the Lesser Sunda marine waters should be performed in smaller spatial scales rather than following that decided by MEOW in the form of MPA. Evidence suggests that conservation at smaller spatial scales ensures that, in comparison to large scales, important characteristics at the regional scale are accounted for. Furthermore, the results also do not conflict with the existing conservation strategy, but rather they complement it. For example, the area of Savu Sea has been designated as a national MPA in accordance with the Minister of Marine Affairs and Fisheries Decree No. 5/2014 (Djumanto *et al.*, 2021).

CONCLUSION

The impact of global climate change is undeniably threatening the bio-physical and chemical processes within marine ecosystem. Hence, an effective and efficient conservation strategy is needed to preserve the function of marine ecosystems. The spatial delineation of the Lesser Sunda Islands is essential for supporting the marine conservation planning efforts in this area. Since environmental characteristics are closely related to the distribution and existence of marine species, it is worth considering these characteristics when partitioning and developing marine conservation areas. The accessible global databases provide numerous marine environmental factors and can be simplified, using PCA techniques, into 6 principal component variables that explained 81.06 percent, and 7 principal components that represent 84.51 percent of the overall raw data variability for the wet and dry seasons, respectively. These components then become the input for the spatial delineation of Lesser Sunda by using FCM. The finding of the FCM analysis suggest that the Lesser Sunda Islands can be delineated into 5 groups during the wet season and 10 groups during the dry season, since it provides the best Silhouette index criterion. The delineated groups obtained from this approach primarily implied Indian Ocean and Bali Sea, Savu Sea and Flores Sea, as well as Banda Sea as distinct clusters. Notably, groups that represented the

Indian Ocean had the highest pH, salinity, and distance to shore, as well as lower nitrates and SST. This is an indication that a single marine conservation area in the Lesser Sunda Islands is not sufficient to adequately represent the physicochemical dynamics in the area, which affect the distribution and diversity of marine species. The delineation suggested in this study showed a certain level of conformity with existing conservation strategies, such as the national MPA of the Savu Sea. However, the identified biogeographic cluster of the Indian Ocean indicates the need for cooperation among countries to effectively manage the MPAs and achieve the various conservation goals. Despite of the used PCA prior to FCM analysis, the algorithm still needs a large amount of time to converge. Thus, modified data dimension reduction techniques and/or fuzzy methods should be considered to solve the issue. Furthermore, the present study only takes into account the environmental variables to delineate the study area to support conservation efforts, while its correlation with marine species distribution is also worth noting.

AUTHORS' CONTRIBUTIONS

E.D. Lusiana, as the corresponding author, contributed by shaping the study concept, data collection, and analysis as well as manuscript preparation. S. Astutik supervised the first author and helped the study design. N. Nurjannah provided a critical review of the manuscript. A.B. Sambah also supervised the first author and performed the study results' interpretation and literature study.

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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

%	Percent
^0C	Degree Celsius
CBD	Convention on biological diversity
CT	Coral triangle
ENSO	El Nino-Southern Oscillation
et al.,	And others
e.g.	Exempli gratia or for example
EW	East west
FCM	Fuzzy c-means
Fig.	Figure
i.e.	Id est or that is
IOD	Indian ocean dipole
IPCC	The Intergovernmental Panel on Climate Change
ITF	Indonesian Throughflow
km	Kilo meter
KMO	Kaiser-Meyer-Olkin
m	Meter
m/s	Meter per second
MARSPEC	Marine spatial ecology
MEOW	Marine ecoregions of the world
mg/m^3	Milligram per cubic meter
MPA	Marine protected area
NS	North south
PCA	Principal component analysis
pH	Potential of hydrogen
PSS	Practical salinity scale

SOM	Self-Organizing Map
SSC	Sea surface chlorophyll
SST	Sea surface temperature
μmol/m³	Micromole per cubic meter
UNCLOS	United Nations Convention on the Law of the Sea

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ORIGINAL RESEARCH PAPER

Performance of sewage sludge reuse in the manufacturing of fired bricks

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ABSTRACT

BACKGROUND AND OBJECTIVES: The disposal of sludge from wastewater treatment plants into the natural environment represents a major danger to the environment and human health. The use of urban sludge as raw material in the manufacture of clay bricks not only reduces the amount of sludge but also transforms it into useful materials. This paper studies the physicochemical, geotechnical, mineralogical, mechanical, and environmental characterizations of earth bricks with the objective of evaluating the performance of the sewage sludge and eventually studying its consistency with natural clay to produce brick samples. The aim of the study is to evaluate the properties of bricks made from sewage sludge, innovating an effective elimination of the urban sludge.

METHODS: Measurements of sludge heavy metal concentrations are made with an inductively coupled plasma on a 63-micrometer fine particle fraction. Organic matter performed by the Walkley-Black assay and the loss on ignition method for comparison. Volatile matter, total nitrogen, moisture content, dryness, pH, methylene blue assay, and carbonate rate were determined using a 2-millimeter Bernard calcimeter by volumetric method. Density, plasticity, liquidity index, and pore distribution were determined using a mercury porosimeter, and the specific surface and granulometric analysis have been established. Mineralogical characterization of sludge by X-ray diffraction, and X-ray fluorescence has been provided for comparative analysis with natural clay. The brick samples were then shaped, dried, fired at 930 Celsius degree, and qualified by tests, including linear and mass shrinkage, porosity, water absorption, density, compressive strength, X-ray diffraction, and leaching.

FINDINGS: The analyses by X-ray fluorescence and X-ray diffraction of the sludge revealed the presence of mineral constituents, including calcite, silica, kaolinite, and dolomite and shows an important amount of silicon dioxide (31.6 percent) and aluminum oxide (11.5 percent). The sludge was classified as fine with a silty-clay character, with a plasticity index of 54.63 percent, and was therefore very plastic, and had trace element concentrations below the authorized standards. A sample containing 10 percent of sludge gives a strength of 25.9 megapascal which is close to that of the control brick. The bulk density analysis of brick sample 1 was 1.57 grams per cubic centimeter and classifies it as a light building material. Above 20 percent of samples substitution, their strength becomes less reliable, due to the large amount of organic matter that burns during firing which creates pores in the finished product.

CONCLUSION: These results suggest that thermal processes limit the leaching of metals and are practically inaccessible to the ecosystem, so the brick cannot harm the environment. As the sludge content increases, the final structure no longer conforms to the control sample. This incorporation of natural clay and sludge allows to obtain a lighter brick than the conventional one. The study suggests that a 10 percent incorporation of sludge allows the production of efficient bricks and reinforces the potential of this valorization technique, which efficiently contributes to the accomplishment of sustainable waste management objectives. By helping reduce waste produced in very large quantities, this study contributes to the protection of the environment and human health.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
62	6	3

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INTRODUCTION

Around the world, debate over environmental issues is an on-going concern. With economic, social, and environmental pressures, the need for natural resources increases over time. Large amounts of waste are generated daily through a multitude of manufacturing processes in various industrial, mining, sanitary, building, and agricultural sectors. The use of recycling processes shows a thoughtful way to protect natural resources and the environment (Martínez-García *et al.,* 2012; Nandi *et al*., 2015). The treatment of wastewater consumed by humans on an industrial and domestic scale inevitably generates significant amounts of sludge, which must be disposed of. Their incorporation as a raw material for the manufacture of clay bricks supports the idea that this sludge can be widely considered as a resource rather than a waste. In the perspective of saving energy and reducing carbon dioxide (CO_2) emissions, the construction industries are looking for efficient, resistant materials with less environmental load while being compatible with the concept of sustainable development. (Rao-Meda *et al*., 2020). Sewage sludge is strongly conditioned by the source of the collected wastewater (Werther and Ogada, 1999; Jarde *et al*., 2003; Singh *et al*., 2004). It is generated at various stages of decontamination of this wastewater altered by different human activities. This sludge is considered a semi-solid and heterogeneous residue, a set of organic and inorganic components, a multi-phase medium of bacteria, and a microbial biomass containing pathogens, nutrients (nitrogen and phosphorus), heavy metals, and a large amount of water 50-60 percent (%) (Zat *et al*., 2021; LeBlanc *et al*., 2009; Chang *et al*., 2020; Yang *et al*., 2015). The sludge in the plant undergoes several treatment processes, including thickening, dewatering, and stabilization through different physical and chemical processes (Liu *et al*., 2013). At this level, the digested sludge is generated, although the moisture content and organic matter content remain high. In Morocco, by 2030, the volume of treated wastewater will reach 900 cubic millimeter per year (mm^3/y), (MAPM, 2011), necessarily generating significant quantities of sludge, with 89,965 cubic meter (m^3) as an annual total in 2014 (PNA, 2008). This pushes the country to engage and initiate the practices of the circular economy by developing any channel of recycling and recovery of waste. Strategies for the treatment of sewage sludge should be considered and implemented so that the process of wastewater treatment takes on its full significance (Moulato *et al.,* 2020), avoiding any contamination of soil, plants, and water. The estimated quantity of sludge worldwide is 45 million tons in 2017 (Zhang *et al.,* 2017). In Europe, it is estimated to be 13.5 million tons in 2020 (Mininni *et al*., 2015). There are several treatment technologies to transform plant sludge into a non-toxic form that respects the ecological balance. These include their uses as resources for fertilizers and bioflocculants (Shi *et al.,* 2017), the production of methane-rich biogas through anaerobic digestion (hydrolysis, methanogenesis) (Collet *et al*., 2017) and the employment of sludge as fuel in thermal processes such as incineration, pyrolysis, and gasification for electricity and heat productions (Abuşoğlu *et al.,* 2017). The energy efficiency of heat recovery systems can reach 37.1% (Quan *et al.,* 2022). The disposal of sludge should be controlled, the moisture content should be less than 60 % and adding solidifiers (magnesium salts, lime, coal ash, aged garbage) is favored. However, this method of disposal has largely demonstrated the most significant environmental impacts. Moreover, its storage requires the occupation of large areas of land, which causes the emission of greenhouse gases. In Japan, 97% of the sludge undergoes reuse in various energy and agricultural sectors and 50% is directed toward recycling it into construction materials (Guangyin and Youcai, 2017). Energy efficiency in the building sector concerns researchers to produce a sustainable ecological material promoting the reduction of energy (Saidi *et al.,* 2019; Limami *et al* 2021). Incorporating 25% of sludge from the plants in the production of bricks can indeed reduce 48.6% of energy consumption during the firing process (Mohajerani *et al.,* 2019). Clay bricks are the most widely used building materials in civil engineering structures (Murmu and Patel, 2018), due to their mechanical and thermal insulation properties (Limami *et al.,* 2019). The high silica (SiO_2) content in sewage sludge improves the physical properties of the brick, which makes this recovery route more environmentally friendly and conservative. A high content of ferric oxide (Fe_2O_3) can be observed in the sludge of the wastewater treatment plant (WWTP), which represents an advantage to the production of

bricks and the saving of iron ore in the manufacturing process (Montero *et al.,* 2009; Zhang *et al.,* 2016). Heavy metals are immobilized in the brick without influencing the environmental and technical characteristics of the final product (Chang *et al.,* 2020; Cusidó and Cremades, 2012; Kadir *et al.,* 2017). Indeed, after sintering, the heavy metals present in the sewage sludge were solidified (Yang *et al.,* 2021) and their leaching is limited. This represents a potential advantage that makes this wastewater treatment plant sludge valorization pathway relevant. Prior to incorporating the sludge in the production of the bricks, it is important to conduct a comparative analysis of the natural clay with the sludge from the WWTP to analyze the possible consistency between the two materials. The amount of sludge to be added, the temperature, and the firing time are major factors that condition the quality of the brick to be designed in terms of strength, bulk density, and linear shrinkage (Rao-Meda *et al.,* 2020; Lin and Weng, 2001). Indeed, the temperature increase from 950°C (Celsius degree) to 1150°C leads to the increase of the bulk density and compacts the particles inside the brick through the formation of crystalline and liquid phases (Luo *et al.,* 2020). Several researchers have strongly endorsed this recovery pathway as it eliminates some of the costly and energy-intensive steps in WWTP sludge disposal and reduces the carbon footprint following the incorporation of a minimum amount of 15% of sludge (Mohajerani *et al.,* 2019). An addition of 6% of liming sludge revealed better technical properties and characteristics (27.5 megapascal for compressive strength, 2.18 grams per cubic centimeter for bulk density, and 10.46% water absorption) (Anik-Hasan *et al.,* 2022). Studies have evaluated additives as raw materials to increase the amount of sludge incorporated, which can be as high as 40% through mixing the sludge with amorphous rice husk ash and Sodium carbonate (Na_2CO_3) (Yang *et al.,* 2021). Paper processing residues (Sutcu and Akkurt, 2009) and glass waste (Dondi *et al.,* 2009) were also evaluated for possible incorporation into bricks. The technique of using waste in the construction industry reduces the need for raw materials and decreases environmental pollution. This recovery generates job opportunities, thus contributing to socio-economic development (Soni *et al.,* 2022). Indeed, the dimensions of sustainable development concept is related to economic, social, and environmental efficiency through better waste management (Łęgowik-Świącik, 2019). A management system must be unique for each area according to its dynamic variables (Weekes *et al.,* 2021). In recent years, several studies have assessed WWTP sludge as raw materials in brick production (Areias *et al.,* 2020; Erdogmus *et al.,* 2021; Wu *et al.,* 2022). In this study, the objective is to testify the feasibility of incorporating the sludge from the Boukhalef plant located southwest of the city of Tangier in the manufacture of clay bricks. The WWTP in question treats urban and industrial waste from the TFZ (tangier free zone), the industrial zone of Gzenaya, and the large neighborhoods in proximity. A chemical, physical, geotechnical, and mineralogical characterization of the WWTP sludge was conducted to compare its composition with that of the natural clay. The sludge was used as a partial substitute for the clay used in the formulation of the laboratory-scale brick samples. To determine the optimum substitution, qualification tests of the different brick samples, including linear drying and firing shrinkage, loss on ignition (mass shrinkage), porosity, water absorption, compressive strength, density, X-ray diffraction, and leaching tests were considered. These measurements were determined and compared to existing standards of the Association Française de Normalisation (AFNOR). The objective is to provide decision makers concerned with the management of sludge from WWTPs in Morocco the relevant elements constituting an identity card of the sludge from the plant of Boukhalef in Tangier for a choice of an effective treatment method. Indeed, the production of an ecological, low energy demand, and resistant building material from sludge reduces the harmful effects of pollution and supports the strategies of circular economy and environmental protection. This study was conducted at the Faculty of Sciences and Techniques of Tangier in Morocco in 2021. It aims to evaluate the properties of bricks made from waste, approving the efficient ability of the urban sludge to be used as raw material for the manufacture of a building element, with improved thermal performance, good quality, and mechanical strength according to the authorized standards, and reduce energy consumption and establish sustainability, thus innovating an effective elimination of urban sludge, which is daily and inevitably produced, by exploiting its physico-chemical properties for the manufacture of a widely

usable material for construction, putting in place an environmental and socio-economic approach.

MATERIALS AND METHODS

Characteristics of sewage sludge

The WWTP of Boukhalef in Tangier treats 11,000 m^3/day of industrial and domestic wastewater and rainwater as effluents, with a tertiary treatment of 5,000 cubic meter per day (m^3/day). The sewage sludge used in our experiment was produced in the purification station of Boukhalef; it is dark gray in color, displayed in a fresh solid form, with an unpleasant odor. This semi-solid was exploited as an additive after dehydration and storage in special skips collected using a stainless-steel shovel and preserved in closed containers in order minimize any contact with air. Sludge samples were also stored at a temperature of 4°C to minimize any bacterial activity that could modify its properties. The sludge was analyzed according to the standards and used as a raw material by partial substitution of clay for the manufacture of bricks. It has 71% water content and undergoes initial pre-treatment through air drying. Representative samples were then homogenized, dried in a steam bath at 40°C for 48 hours. The sludge is sieved and conserved to obtain a constant mass, eliminate impurities, reduce the organic fraction, and guarantee a balanced humidity before performing the various analyses. To evaluate the suitability of this sludge to be incorporated in the composition of the brick, the complete characterization of the most relevant parameters must be performed first. X-ray diffraction (XRD) allowed to identify the crystalline phases of the sewage sludge and their sizes using a Spinner model apparatus with a copper anticathode and generator with a voltage and consumption of 35 kilovolt (KV) 30 milliampere (mA). A scan from 4° (degree) to 84° of the 2 Θ (theta angle) was performed in each case at 0.02° per second. X-ray fluorescence (XRF) spectrometry also allowed to quantify and qualify the chemical elements present in the sludge such as silica (SiO_2), calcium oxide (CaO), ferric oxide (Fe_2O_3), alumina (Al_2O_3), titanium dioxide (TiO_2), magnesium oxide (MgO), sulfur trioxide (SO_3), phosphorus pentoxide (P_2O_5), and sodium oxide (Na_2O). It is important to know and monitor the concentrations of heavy metals in the sewage sludge in order to determine its pollution level. This analysis is performed with an Inductively Coupled Plasma (ICP) Atomic Emission Spectrometer on a fine particle fraction of 63 Micrometer (µm) which contains the highest concentration of metals. The sample transmitted to the plasma undergoes various stages of decomposition, atomization, and ionization. The intensity of the lines emitted by the atoms and ions generated is measured. The granular distribution of fine grains with a diameter lower than 80 (µm) was measured through laser granulometry to determine the proportion of the various solid constituents of a soil according to their size. The specific surface of the sludge was measured after thermal treatment at 105°C using the Brunauer–Emmett–Teller method of physical adsorption of gas molecules on a solid surface as well as the methylene blue method, which measures the fineness of the grind material. In order to adjust the moisture content of the sludge and the clay for an adequate consistency and plasticity for extrusion, it is necessary to measure the plasticity index (Pi) by the Atterberg limits, which represents the range of water content in which the sludge is in the plastic state. The limits of liquidity (LL) and limits of plasticity (PL), Pi = LL – PL, have been determined with a cone penetrometer according to the French standard (NF) P94-052-1, and NF P94-051. To have access to the distribution of the volumes and sizes of the sludge pores, the mercury porosimeter measures them through the diameter of the pore entrance. Basic chemical characteristics were determined; pH to estimate the neutralization potential of the sludge, dryness, moisture and electrical conductivity a quick way to assess the salinity of the organic substrates. The volatile matter is measured by the weight lost from the sample after calcination for 2 hours at 525°C to determine the organic components that can be found in gaseous form in the atmosphere. The percentage of total nitrogen dissolved in the sludge was determined, including organic and ammoniacal, which allows to quantify the sludge level pollution. The carbonate content was measured on a 2 millimeter (mm) sieved sludge by the action of hydrochloric acid (HCl) on the calcium carbonate ($CaCO_3$) in the sludge; a high carbonate content makes the sludge alkaline and favors all fixation modes. The organic matter characteristic of sludge was determined by the "Walkley-Black" dosage method and directly through the loss on ignition (LOI) method after thermal treatment at 500°C for 16 hours. This study will allow us to know if it has common properties with natural

Fig. 1: Samples of fired test bricks

clay so as to produce bricks of the same quality as the conventional ones.

Comparison of raw materials

The annual production of bricks requires significant amounts of clay (3.13 billion cubic meter of clay soil) (Mohajerani *et al.,* 2019). This means that adding a substitute such as sewage sludge to the clay could be a practical and sustainable alternative, reinforcing the concept of the circular economy through the management of both resources and waste. The variable composition of clay allows its incorporation into several types of waste (Liew *et al.,* 2004). Before mixing the sludge with natural clay, a comparative analysis of the two components must be conducted. The control clay was provided from the brick factory, Al Andalous, located in the region of the city of Tangier. X-ray diffraction and X-ray fluorescence indicate the presence of existing mineralogical phases of the clay, and the chemical composition of major elements. The contents of organic matter and calcite were measured and compared. The granulometric distribution analyzed by laser granulometry determines the size of particles smaller than 80 (µm) (Agostini, 2006) present in the clay. This factor can affect the drying and firing properties and the formation characteristics of the clay. The specific surface is considered in the comparative analysis of the clay and the sludge. It is influenced by the parameters indicated before and the shape and surface state of the grains. The plasticity limit, Atterberg liquidity, and plasticity index were examined and compared.

Production of the sample mixture

The preparation of cylindrical bricks, 30 millimeter (mm) in diameter and 30 millimeter (mm) in length, was carried out at the laboratory scale, and eight different mixtures were obtained: Indicator, Brick1 (B1), Brick2 (B2), Brick3 (B3), Brick3.5 (B3.5), Brick4 (B4), Brick5 (B5), and Brick6 (B6). Based on the results previously obtained and to have a better performance at the level of extrusion, the quantity of water used for the preparation of the samples of bricks varies between 21% and 30.5%. For the reference brick, the quantity is only 10%. The mixtures of sludge with clay were made with a substitution rate of 0%, 10%, 20%, 30%, 35%, 40%, 50%, and 60%. The brick samples prepared at different rates were compared with the reference sample while using the existing standards. Initially the sludge was dried at 105°C and crushed using a ceramic ball mill and then sieved through 2 (mm) before being combined with the brickyard clay according to the different substitutions proposed. Using a mixer, the two materials were homogenized in dry conditions before being moistened and extruded, powered by an electric box. It continuously manufactures the products by transporting the material from the circular entry section (feeding hopper) to the rectangular exit. Drying is then conducted to eliminate the water contained in the

shaped products, under ambient conditions and with precision to obtain a shape without surface or volume defects while avoiding cracks. The test bricks do not have their true qualities yet. It is necessary to allow them to acquire their mechanical strength, stability, and resistance to weathering and to subject them to firing at elevated temperatures. The samples made are subjected to a system of firing of up to 930°C in a tunnel kiln maintained for 48 hours. The shape of the final sintered bricks obtained after cooling to room temperature is shown in Fig. 1.

Characterization of bricks

The fired and unfired bricks underwent a series of experiments, including qualification tests and evaluation of the characteristics, and the behavior of materials produced for use in construction. The linear drying shrinkage was measured as the ratio between the difference in length before and after drying and the initial length (Demir, 2008; Mezencevova *et al.,* 2012). The lengths of the samples were measured with a caliper. As for the linear firing, it is related to the sintering process. It is measured to determine the action of heat on the clay material, which causes physical and chemical phenomena and creates a firing shrinkage. The porosity of bricks was measured, and it is one of the most relevant and important parameters in the characterization of the brick. It directly influences the thermal mechanical properties of the material, including strength, absorption, and permeability. The water absorption has also been examined; it determines the ability of the brick to absorb water, it is proportional to the porosity, and it has a close relationship with the density. The degree of water absorption is a function of the size and distribution of pores in the brick, and its durability and strength are strongly influenced by this parameter (Esmeray and Atıs, 2019). Compressive strength represents the maximum stress allowed by a material subjected to a crushing load, expressed in megapascal (MPa) and is considered as a good indicator of the quality of fired materials. Scanning electron microscopy (SEM) images were taken to identify the differences in the pore and crack structure of the different brick samples. XRD analysis was considered to study the mineralogical transformations of the control brick compared with the other samples with different substitution rates. The leaching test is performed to evaluate the potential of pollutant release to the outside (natural) environment. The fired bricks are crushed, ground, and stirred in water for 24 h with a Liquid/Solid (L/S) ratio equal to 10 according to the procedure described in the NF European norm (EN) 12457, 2002. After filtration, the leachates are analyzed in the laboratory using the ICP technique.

RESULTS AND DISCUSSION

Analyses applied to raw materials

The results of the examination of the mineralogical phases present in the raw materials used for the manufacture of bricks at the laboratory scale are demonstrated in Figs. 2 and 3. XRD reveals the presence of the spectra of mineral constituents, including calcite ($CaCO_3$), silica (SiO_2),kaolinite ($Al_2Si_2O_5(OH)_4$), and Dolomite ($CaMg(CO_3)_2$) in the WWTP sludge. The observed mineral composition within the sewage sludge is similar to that of natural clay used by the brickwork. XRF shows that the sludge is mainly composed of silicon dioxide (SiO_2) and aluminum Oxide (Al_2O_3) with respective percentages of 31.6% and 11.5%. It also contains low contents of 5.75% CaO, 3.73% Fe_2O_3, 2.09%MgO, 2.71% P_2O_5, 1.93% SO_3, and other elements in smaller quantities. The predominant oxides in common with the clay are silicon dioxide, aluminum Oxide, iron oxide and CaO with respective percentages of 58.1%, 16.9%, 3.73%, and 5.38%. The combination of 15% sludge with shale revealed very comparable results with a value of 25.60% SiO_2, 12.0% Al_2O_3, and 5.13% Fe_2O_3 (Wu *et al.,* 2022). Al_2O_3 is related to plasticity, and its content in the studied sludge is within the allowed limit. The proportion of SiO_2 of the WWTP is lower than that of clay but still significant. The content of Fe_2O_3 allows the sludge to be considered as clay with a medium content of coloring oxide. Calcium oxide does not exceed the upper limit tolerated by the standards; its presence is due to the quantities of lime used in the sludge dewatering process in the WWTP. The mineral and chemical composition of sludge and clay is beneficial for the sintering and solidification of the final product. There is chemical and mineralogical affinity between the sewage sludge and the clay body (8.83% Al_2O_2, 14.26% SiO_2, and 7.78% Fe_2O_2) (Areias *et al.,* 2020). Among the relevant parameters in the analysis of the possible coherence between clay and sludge is the <80 m particle size of both materials. The median particle diameter 50 (D50)%

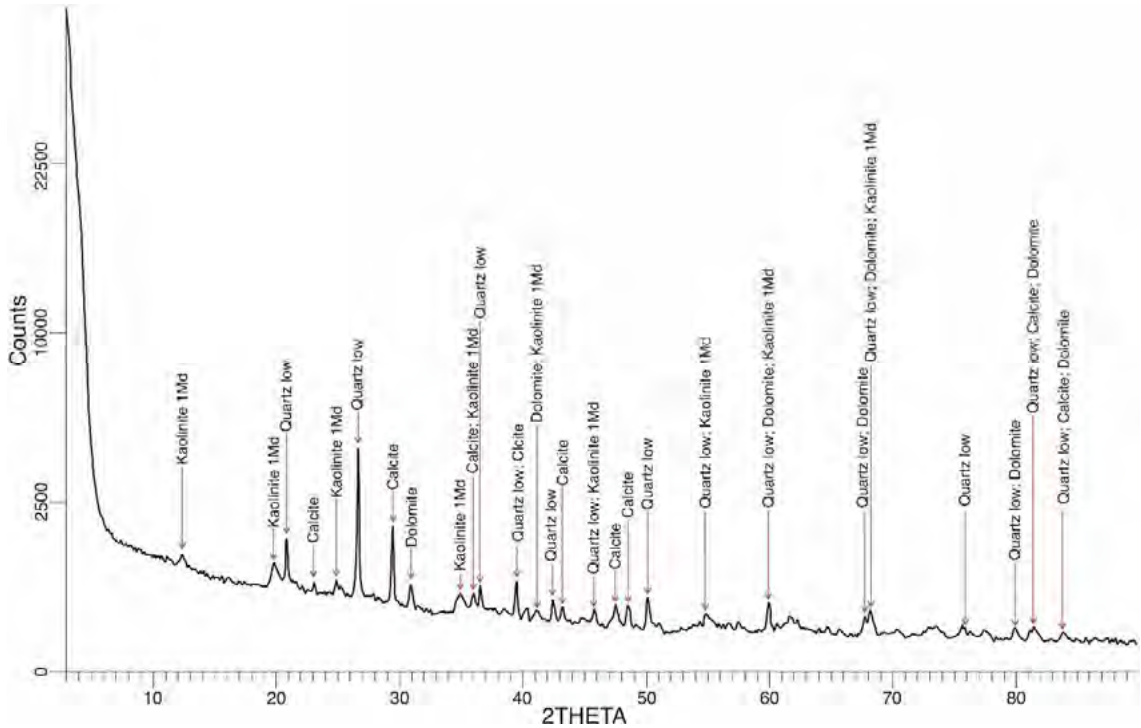

Fig. 2: X-ray diffraction of the studied sludge

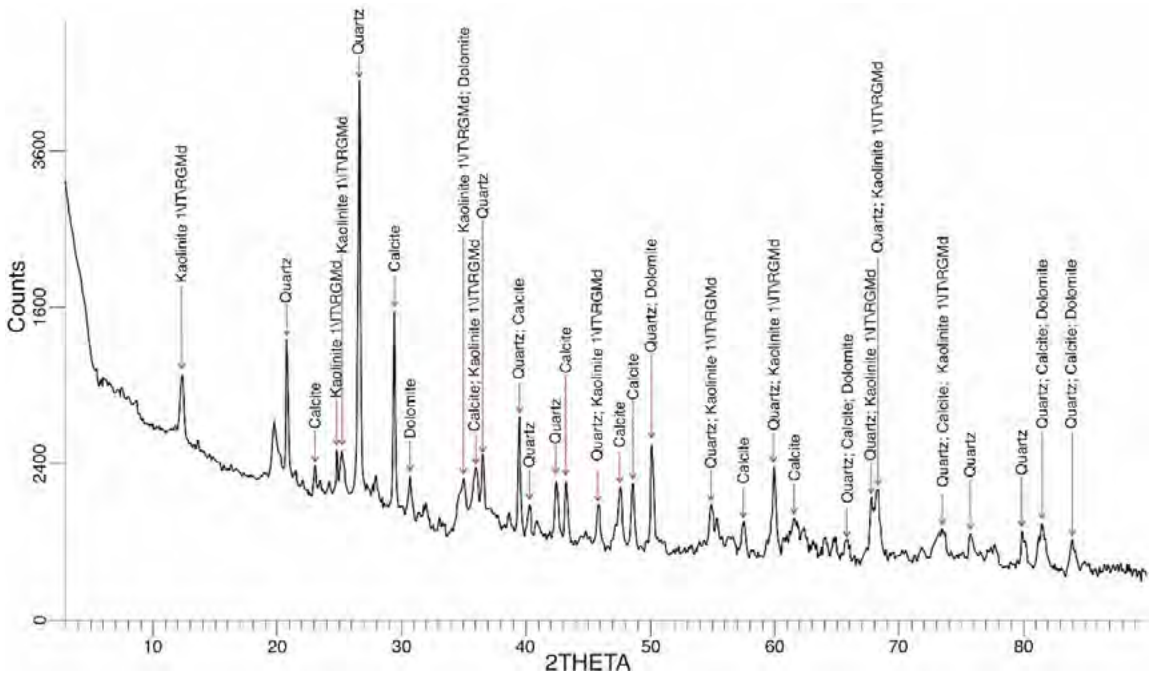

Fig. 3: X-ray diffraction of natural clay

Table 1: The used wastewater treatment plant sludge properties and composition

Parameters	WWTP Sludge properties
pH value	8,32
Moisture content (40°C)	51,57%
Density	1.69 gram per cubic centimeter (g/cm^3)
Electrical conductivity	3,34 millisiemens per centimeter (ms/cm)
Volatile matter	39,67%
Carbonate content	7,97%
COD/BOD	1,8 milligrams of oxygen per liter (mgO$_2$/L)
Total nitrogen	0,845%
Organic matter	32.5%
Atterberg Liquid limit (%)	114,730%
Atterberg Plastic limit (%)	60,100%
Cadmium (Cd)	2,14 milligram per kilogram (mg/kg)
Chromium (Cr)	366,48 (mg/kg)
Copper (Cu)	2,14 (mg/kg)
Lead (Pb)	79,18 (mg/kg)
Nickel (Ni)	20,33 (mg/kg)
Zinc (Zn)	411,96 (mg/kg)
Loss on ignition	37,5%

of the clay and the sludge studied by laser particle sizing shows a very similar particle distribution of 30.9 µm and 26.669 µm, respectively. The <63 µm fraction of the sludge is 98.95%, with a methylene blue value between 2.5 and 6. These results explain that the sludge is thin, with a clayey silty character, is of average plasticity, and with a total specific surface of 83.72 square meter per gram (m^2/g). The specific surface of the clay, 148.60 m^2/g, is much higher than that of the WWTP sludge, which agrees with granulometric analysis. The values of the Atterberg limits of the Al Andalusian clay and the sludge show that they are classified as very plastic materials (Pi > 40). The Pi of the sludge is 54.630% and that of the clay is 63.172%.

The sludge can be incorporated into the formation of bricks without losing its plastic behavior. The sludge of the studied WWTP is richer in organic matter than the natural clay; it contains 32.50% as opposed to 3.36% for the clay. This result is due to its nature as an activated sludge. The calcite contents for both materials are very comparable (8% for the clay and 7.97% for the sludge). Nevertheless, the high content of organic matter leads to an increase in porosity and a low adhesion force, which influences the thermal and acoustic properties of the final product through the condensation of porosities (Cusidó *et al.*, 2003). Indeed, its presence in the sludge reduces the energy demand considerably during the firing process of the brick (Ukwatta and Mohajerani, 2017) by releasing its calorific value during combustion. The results show that the sludge is rich in organic matter since it is an activated sludge. This high content is also demonstrated by the high percentage of loss on ignition (39.99%). The sewage sludge has a high porosity of 48.7%. Nevertheless, the process of sintering the bricks completes the crystallization of the material through the increase of temperatures, which can reduce the porosity of the final product (Wang *et al.*, 2019). Table 1 shows the results of basic chemical and physical parameters measured for sludge, and those of the heavy metal determination to evaluate the polluting potential of the sludge studied. The analyzed sample presents concentrations in trace elements lower than the standards retained and authorized for their valorization in agriculture,

Table 2: Values of the plasticity index and specific surface of the realized mixtures

Substitutions	Plasticity index %	Specific surface (m^2/g)
Indicator	63,172	115,115
B1 (10%)	115,593	98,371
B2 (20%)	115,425	94,185
B3 (30%)	87,492	89,999
B3.5 (35%)	81,580	87,906
B4 (40%)	77,048	73,255
B5 (50%)	69,677	66,976
B6 (60%)	66,977	62,79

which encourages using this sludge in a building material without any prior treatment. Certainly, it is not possible to conclude that there is a total absence of metallic pollution in the sludge. Some may be higher than others but still in accordance with the standards (Kadir *et al*., 2017). The nature of sludge was determined by pH as defined in the NF X 31-103. The pH value demonstrates that the sludge is of a basic nature. The sludge is composed of water and dry matter and is generally characterized by high water content. Surface water content represents total moisture and it is determined by the drying of samples at 40°C and 105°C until the mass is constant according to NF X 31-101 and NF X 31-102, respectively.

Mixture plasticity and specific surface

The plasticity allows to mold, shape, and keep a constant volume brick shape during drying and firing. The measurement of the mixture plasticity provides a first insight into its quality and determines its consistency. In the literature, it has not been determined yet how the sludge affects the plasticity and consistency of the mix during extrusion (Zat *et al.,* 2021). The Pi and workability of the mixture decreases as the substitution rate of clay by sludge increases. Indeed, the plasticity limit is inversely proportional to the amount of sludge added in the mixture (Weng *et al.,* 2003). The complete permeation of the necessary added water is a factor that controls the plasticity of the sludge and clay and avoids structural defects during the process. The purpose of the Atterberg limit measurements is to identify the water content in the mixture. As the sludge content increases, so does the water requirement. An increase in the addition of water are due to the presence of big amounts of organic matters in sludge. The organic substances in soil have a high absorptive capacity of water (Demir, 2008). The results obtained reveal very interesting Pi percentages (115.59%–66.97%) for the different substitution rates. The clay minerals present in the clay ensure its cohesion and ability to undergo deformation hence the high percentages of plasticity in the control sample as well as B1 and B2. The specific surface of the mixture of the two raw materials was carried out according to the standard NF P94-068 to measure the total surface (external and internal). This parameter also decreases with the increase of the substitution rate, as shown in Table 2. Plasticity represents an important characteristic of the bricks. Inadequate plasticity can result in extrusion failure and development of heterogeneities in the brick body, which can result in weak mechanical properties (Mezencevova *et al.,* 2012).

Analyses of brick samples

After characterization of sludge and clay, the tests have been performed for brick sample manufacturing. Different amounts of sludge, 0% (indicator), B1 (10%), B2 (20%), B3 (30%), B3.5 (35%), B4 (40%), B5 (50%), and B6 (60%) were chosen. Prior to forming bricks, raw materials (natural clay and sludge studied) were dried, crushed, sieved, and mixed well in the dry state after adding water (10%, 21.5% 24.5%, 25.0%, 27.0%, 27.5%, 30.0%, and 30.5%). All the parameters and tests carried out were based on the existing standards. To evaluate the behavior of the bricks formed to be applied in construction, it is necessary to apply qualification and characteristics tests.

Linear shrinkage to drying and linear shrinkage to firing:

During the drying process, the water contained in the mixture is extracted from the clay materials. Tensions within the material occur, and deformation or cracks may appear. The linear drying shrinkage

(B1 8.19%, Indicator 8%) depends mainly on the clay mineralogical composition, the texture of the paste shaping, the amount of water used, and the percentage of the degreasing material. The results presented in Fig. 4a and b show that the shrinkage amplitude of the brick samples was affected by the moisture content of the raw mix, which is related to the rate of substitution. Indeed, this parameter varies according to the content of sludge added to the mixture; when the substitution rate increases, the water content increases, as well as the drying shrinkage. The linear shrinkage on drying takes a value of 8% and increases to 13.6% and 26.5% by adding about 5%–10% of sludge (Zat *et al.,* 2021), which is relatively comparable to the results of the study. The action of heat on the clay material causes physical and chemical phenomena and creates a shrinkage on firing, which also increases with the substitution rate of the sludge. The linear firing shrinkage (B1 10.22%, Indicator 10%) is mainly related to the sintering phenomenon, which in turn depends on the particle size of the sludge. Being finer than the clay, the sludge responds better to sintering, which makes the shrinkage more important. Indeed, the fraction of organic matter contained in the sludge has a significant influence on the linear shrinkage of the brick.

Heat loss

In the light of the obtained results, Fig. 4c shows that the heat loss percentage of fired test bricks on ignition increases in the same direction with the increase of the substitution rate at 10.59% and 12.48% for the indicator and B1, respectively. This is due to the decomposition of calcite and the removal of organic matter present in the sludge during the firing of the bricks. The loss on ignition varies with the curing temperature of the material and depends on the organic matter contents of the sludge. It is related to clay mineral dehydroxylation, oxidation of organic matter, carbonate decomposition, sulfides, and hydroxides. Upon the addition of sludge in the mixture, the weight loss apparently increased because of the loss of contribution of organic matter in the sludge. Furthermore, the brick weight loss on ignition also depends on the inorganic substances in both clay and sludge being burnt off during the firing process (Luo *et al.,* 2020).

Porosity

This parameter directly influences the mechanical strength, water absorption, and permeability of bricks (Samara, 2007). It is important to determine the porosity of bricks for the indication of their quality, durability, as well as for dimensional stability to obtain a final product without defects. The occurrence of open pores on the bricks significantly affects its mechanical performance (Hegazy, *et al.,* 2011). The addition of the studied sludge leads to an increase in the porosity of the bricks compared with the control sample as well as for all proportions suggested (Fig. 4d). This is attributed to the large amount of organic matter present in the sludge, which after undergoing thermal destruction during cooking at 930°C, creates pores. The presence of carbonates is also a factor contributing to the formation of pores, which after decomposition releases carbon dioxide and accentuates the phenomenon in question. Samples B1 and B2 have a respective porosity of 20.6% and 22.97% compared with the control value of 16.88%. Studies show that elements composed of SiO_2 have a high porosity percentage and a lower mechanical strength (Singh *et al.,* 2018). Incorporation of 5%–20% sludge by weight of clay can decrease around 6% porosity in the brick specimen (Amin *et al.,* 2022). Nevertheless, the pores present in the brick improve the thermal insulation properties of the material (Mohajerani *et al.* 2019). To achieve adequate porosity, the addition of 10%–20% WWTP sludge is most appropriate.

Water absorption

According to the study, the coefficient of water absorption of the bricks increases with the addition of the sludge proportions (Fig. 4e). Indeed, the addition of biosolids in the mixtures increases the porosity of the bricks, which generates a more important water absorption. It can be deduced that the size and distribution of pores in the brick define the degree of the material and its capacity of water intrusion. This indicator of brick strength is strongly related to the temperature reached during sintering; the water absorption increases with the sludge content and with the decrease of the firing temperature, which directly affects the durability of the brick (Weng *et al.,* 2003). Amounts higher than 15% might surpass the maximum of 22% for water absorption (Areias

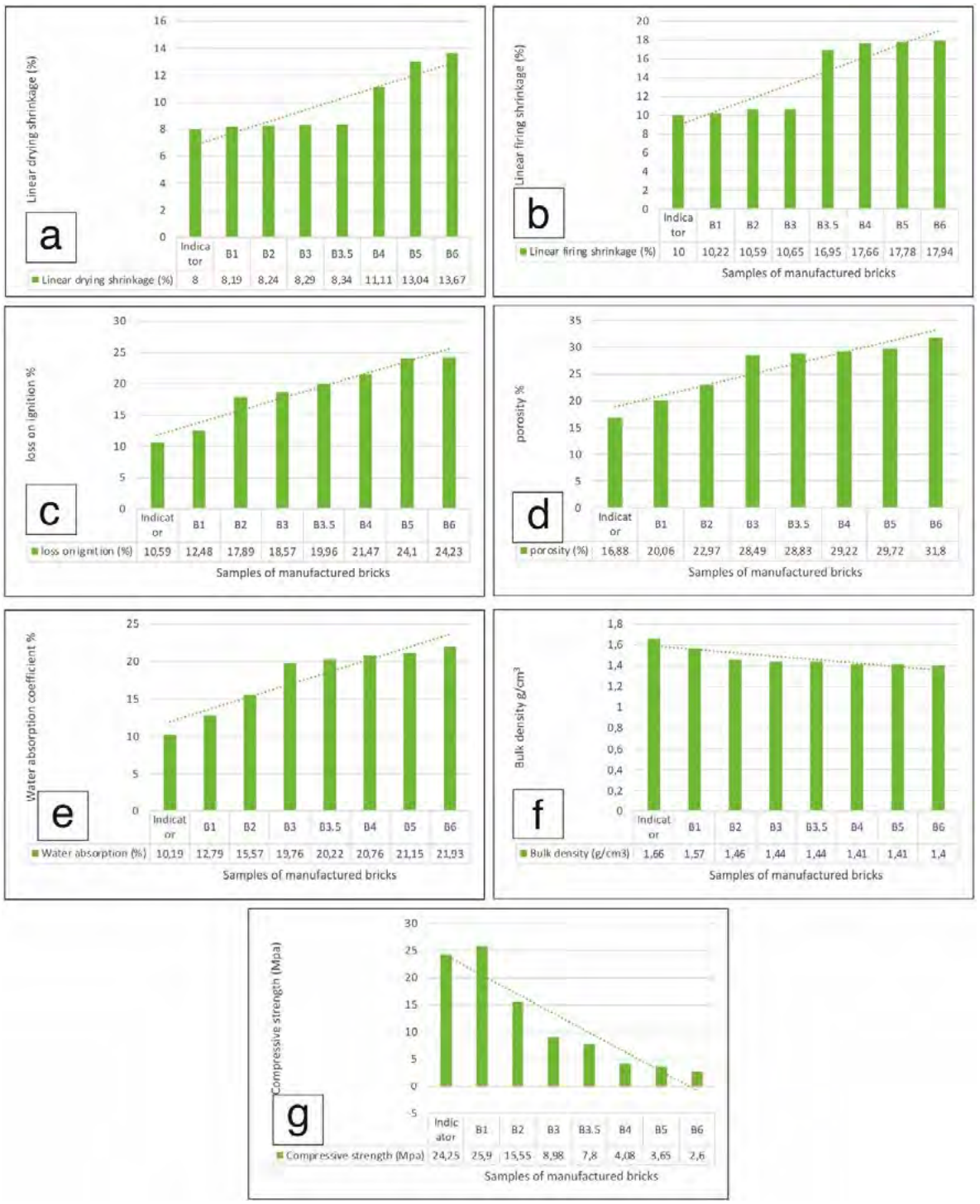

Fig. 4: Qualification tests of the different substitutions of the prepared sludge–clay bricks, B1(10%), B2(20%), B3(30%), B3.5(35%), B4(40%), B5(50%), and B6(60%) compared with the control sample. (a) linear drying shrinkage (%), (b) linear firing shrinkage (%), (c) loss on ignition (%), (d) porosity (%), (e) water absorption coefficient (%), (f) bulk density (g/cm^3), and (g) compressive strength (MPa).

et al., 2022). The water absorption coefficients of tested bricks B1 and B2 do not exceed 12.79% and are remarkably close to the indicator clay sample (10.19%).

Bulk density

As shown in Fig. 4f, the bulk density decreases with increasing sewage sludge rate. These results are consistent with the values of porosity and water absorption. The addition of the sludge makes the brick porous and less dense due to the combustion of organic matter (Frar *et al.,* 2014). Nevertheless, the value of sample B1 (1.57 g/cm^3) does not exceed the recommended margin of 1.75 g/cm^3 and is very comparable to the indicator sample (1.66 g/cm^3). A value of 1.70 g/cm^3 bulk density was mentioned by adding 25% water treatment sludge and increases up to 2.05 g/cm^3 by reaching 100% (Erdogmus *et al.,* 2021). As the temperature increases, the bulk density of the bricks in the sludge–clay mixture increases. The effect of the sludge can be observed through water absorption, porosity, and density, which are closely related. Although the bulk density remains approximately constant from sample B3.5, the sludge additions increase the porosity and water absorption. The temperature increases from 950°C to 1150°C, which can cause the elevation of bulk density and compact the particles inside the brick through the formation of the crystalline and liquid phases (Luo *et al.,* 2020).

Compressive strength

Among the analyses elaborated to define qualification of the produced bricks, the most reliable data are obtained during the pressure resistance tests. All the samples were assessed for pressure after curing. The smallest resistances, 3.65 and 2.6 MPa are recorded for the highest sludge additives. The values in Fig. 4g show that the brick containing 10% (B1) sludge gives a strength of 25.9 MPa, which is close to that of the control brick at 24.25 MPa. Above 20% (B2) substitution, the strength of WWTP sludge bricks becomes less reliable 15.55 MPa due to the large amount of organic matter that burns during firing and creates pores in the finished product. This makes the brick more porous, lighter, and less strong. The release of gases and the thermal decomposition of the organic matter make the brick brittle. The compressive strength of brick samples with 10 % dried sludge and 10 % incinerated sludge could reach up to 70 % and 98 % of the value for the normal clay bricks, respectively (Chang e*t al.,* 2020). The strength of the bricks increases with the firing temperature. If the duration is between 2h and 8h, the desired strength can be obtained (Murmu and Patel, 2018). With increasing temperature, the compressive strength is improved by refining the pore structure. This parameter reached 34.4 MPa in a study that combined 15% sludge with 84% shale (Wu *et al.,* 2022). Compressive strength increased remarkably (27.50 MPa) in a study incorporating 6% of liming sludge (Anik-Hasan *et al.,* 2022).

Morphological images by SEM

The morphological analysis of the different samples shows the presence of pores. The comparisons have been made based on the control sample (100% clay). The pore distribution becomes more pronounced from a substitution rate of 20%. The resulting microphotographs corresponds to the different substitution rates proposed in the study. As shown in Fig. 5, the samples hardened at 930°C, and as the sludge content increased, the final structure did not conform to the control sample. Indeed, the texture of the bricks has changed considerably due to the significant condensation of the pores and the growth of their size and distribution. A decrease in the crystalline mineral fraction, including SiO_2 present in the clay, occurs with the addition of sludge, which creates open pores and decreases the mechanical strength of the brick (Limami *et al.,* 2019; Hegazy *et al.,* 2011). An excellent quality brick can be obtained from a mixture of clay (90%) and sludge (10%) dried at 105°C and sintered at 930°C.

XRD

Since the strengths of the control and B1 sample are very comparable, the study focused on analyzing the mineralogical transformations of these two brick samples using XRD analysis. The spectra in Fig. 6 shows the appearance of hematite (Fe_2O_3) and the persistence of quartz (SiO_2) being the main crystalline phase for the two bricks manufactured (Indicator and B1) with minor modifications with respect to the other constituents.

Brick leaching (Environmental study):

Table 3 shows that the concentrations of heavy

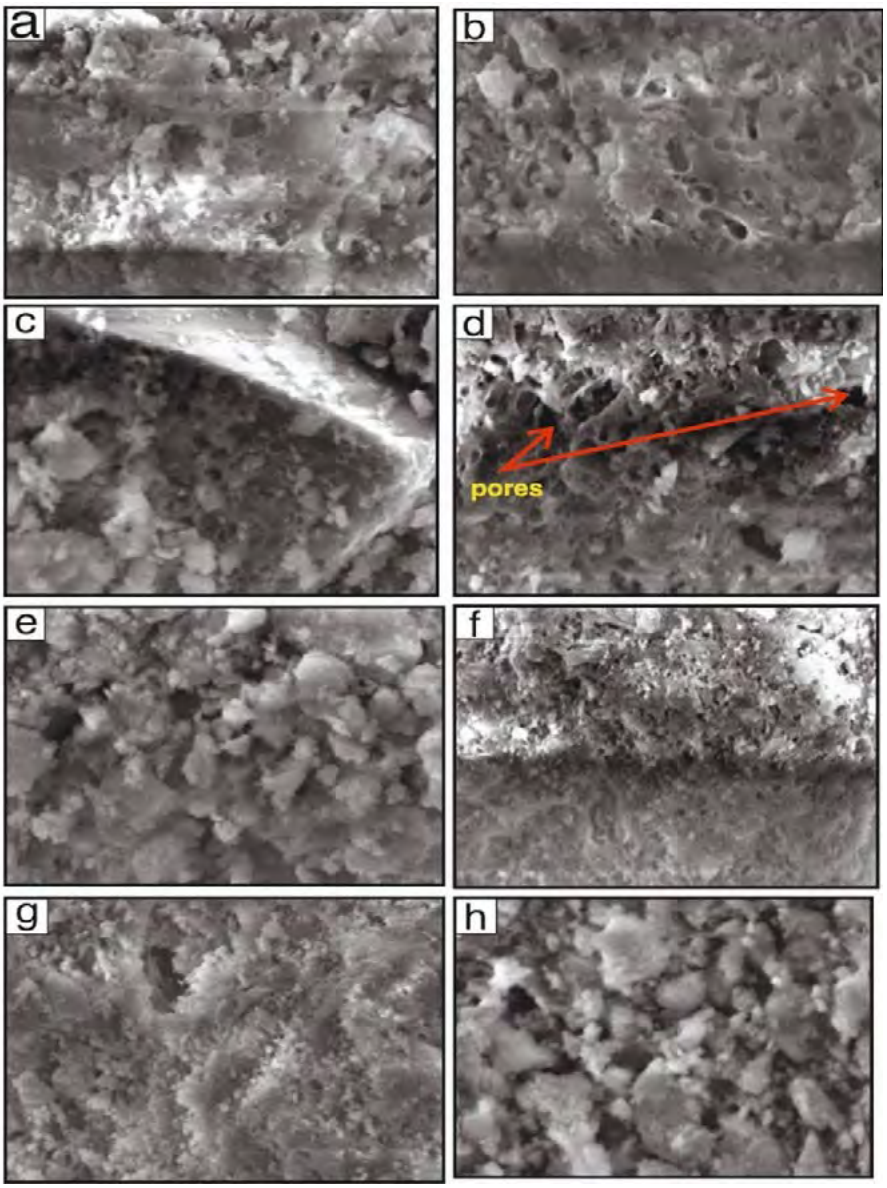

Fig. 5: Scanning electron microscopy images of fired bricks: a (indicator), b (B1), c (B2), d (B3), e (B3,5), f (B4), g (B5), and h (B6)

metals are below the permissible limit values for landfills. During the sintering process, most of the metal contaminants were fixed in the new minerals and converted into stable compounds and immobilized in the brick matrix during firing (Bernstein *et al.,* 2002). Thermal processes make the metal less leachable, thus the brick cannot harm the environment or human health (Wang *et al.,* 2012). In addition to the stabilization and limitation of heavy metal leaching through the solidification of bricks, dewatering of sludge is not mandatory, leading to the saving of energy (Świerczek *et al.,* 2018; Mladenovič *et al.,* 2017). According to other studies, metal leaching is insignificant for fired bricks incorporating sludge (Anik-Hasan *et al.,* 2022; Kulkarni *et al.,* 2019).

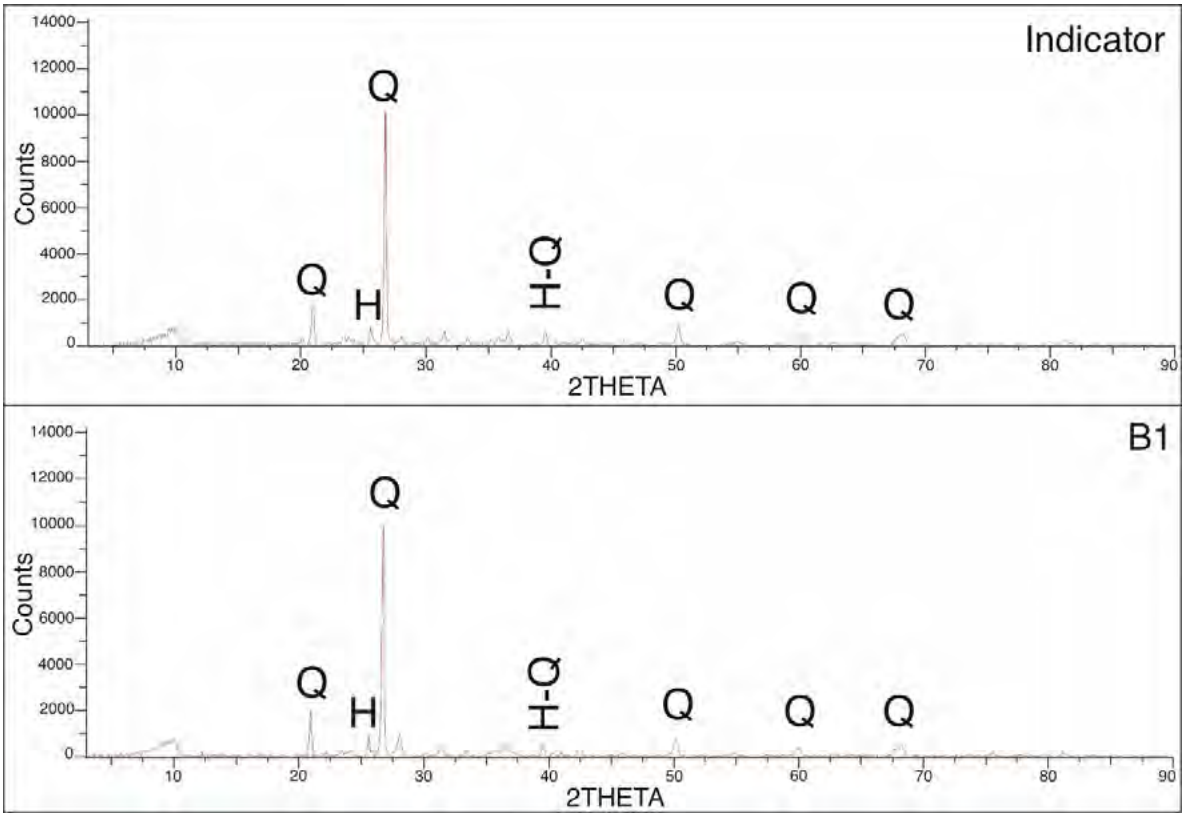

Fig. 6: X-ray diffractograms of the indicator brick sample containing 100% clay, and the B1 sample with 10% sewage sludge.

Table 3: Trace element concentrations milligram per liter (mg/L) in leachate from fired test bricks.

Brick samples	Arsenic	Cadmium	Chromium	Copper	Nickel	Lead	Zinc
B1 (10%)	≤0,01	≤0,005	0,075	0,04	0,037	≤0,005	≤0,008
B2 (20%)	≤0,01	≤0,005	0,085	0,04	0,038	≤0,005	≤0,008
B3 (30%)	≤0,01	≤0,005	0,013	0,05	≤0,005	≤0,005	≤0,008
B3.5 (35%)	≤0,01	≤0,005	0,138	0,05	≤0,005	≤0,005	≤0,008
B4 (40%)	≤0,01	≤0,005	0,077	0,04	0,028	≤0,005	≤0,008
B5 (50%)	≤0,01	≤0,005	0,106	0,04	0,026	≤0,005	≤0,008
B6 (60%)	≤0,01	≤0,005	0,099	0,05	0,026	≤0,005	≤0,008
Level 1[(a)]	0,5	0,04	0,5	2	0,4	0,5	4
Level 2[(b)]	2	1	10	50	10	10	50

[(a)] Limit values for waste in landfills for inert waste L/S=10.
[(b)] Limit values for waste in non-hazardous waste landfills L/S=10

CONCLUSION

The results from the present study support the idea that the WWTP sludge of Boukhalef in Tangier northern Morocco is suitable to be valorized into a construction material. The chemical composition, pollutant potential, physical, environmental, geotechnical characterization, and the mineralogical parameters indicate the feasibility of the incorporation of the sludge with clay as raw material in the production of clay bricks by extrusion, and

give a global idea about the studied sludge. Indeed, the chemical (% major elements) and mineralogical composition of the sludge and those of the clay used for the manufacture of construction products are consistent and comparable and in compliance with the standards. The values found reported that the sludge has an assorted composition, notably SiO_2 with a concentration of 31.6%, 5.75% CaO, 3.73% Fe_2O_3, and traces of other elements. The WWTP sludge can be considered as a potentially interesting addition to the manufacture of bricks. The Pi results show that the sludge has a highly plastic nature (Pi > 40), while the clay is classified as plastic clay (15 < Pi < 40). Based on the methylene blue values, sludge studies are classified as a silty–clayey soil, while clay is classified as a clay soil. These empirical tests provide essential data on whether the sludge is plastic, can form a binding paste, is impermeable, and is compact like clay. The production of cylindrical bricks was conducted for mixtures of sludge and clay with different substitution rates. After sintering, the fine mineral particles increased and are bound together to form a compact product. According to the results obtained, the porosity, water absorption, and the bulk density are dependent on the substitution rate of the sludge. Firing time, temperature, and the proportion of sludge added are the factors that initially determine the quality of the building brick. The organic content of the sludge has a significant effect on the strength and performance of the material. The optimum substitution rate of clay in the brick formulation by sludge was evaluated by means of physical and mechanical tests. These obtained results ensure that the mechanical performance of the samples is similar to that of the reference brick for a substitution rate of 10% (B1), and from 20% (B2) of substitution, the compressive strengths of the sludge bricks decreased. This can be attributed to the high presence of organic matter in the sludge, which increases with the substitution rate; this burns during the firing process due to thermal destruction and tends to be depleted and create pores in the finished product. These increase the humidity of the brick and weaken its strength. As a result, the brick becomes more porous, exceptionally light, and less resistant. The average results of the tests of the resistance of the brick are situated between 25.9 MPa and 15.55 MPa for an incorporation not exceeding 20%. The morphology of the brick samples is unsuitable and not consistent with the control product except for B1 containing 10% of sludge, which is remarkably similar to that of the reference sample. Based on the most noteworthy results, an addition of 10% sewage sludge to 90% natural clay was selected as the best choice for this incorporation. Other reviews have selected between 10% and 15% sludge to be incorporated or even more, depending on the nature of the biosolid used and the addition of further additives such as shale, recycled glass, sludge ash, and wood. The leaching test showed exceptionally low concentrations of trace metals in the brick leachates confirming the immobilization of these elements in the ceramic matrix during firing, which represents a potential environmental benefit. These results demonstrate that the sludge is not a hazardous waste, noting the absence of metal pollution, which encourages using this sludge in a building material without any prior treatment. The WWTP sludge is a promising source of local raw material for the fired brick manufacturing sector. The incorporation of natural clay and sludge allows to obtain a lighter brick than the conventional one. This study shows an economically and ecologically innovative method for the elimination of sludge by recycling it into ceramic materials. In Morocco, bricks are often used in the construction of buildings, and the sludge is mostly landfilled or used for agricultural spreading, which are the least favorable pathways. The purpose is to evaluate the production of bricks with waste additive, innovating an effective way of urban sludge elimination, exploiting its properties for the manufacture of a widely usable element for construction. This technique of station's sludge valorization in an excellent quality brick proves to be interesting for an operational and clean choice of elimination contributing to the management of a waste inevitably produced, putting in place an environmental and socio-economic approach meeting the requirements of sustainable development and circular economy.

AUTHOR CONTRIBUTIONS

K. Moulato as the corresponding author, contributed to the conceptualization of the article, prepared all the figures, worked on the interpretation of results, wrote the original version, participated in the analysis of the raw materials used as well as in the manufacture of the bricks in the laboratory, and

performed the data analysis. M. Ammari provided the necessary resources, adopted the methodology that was followed, and supervised the execution of the work and the final article. L. Ben Allal revised and edited the paper, made the final visualization, and gave the final suggestions.

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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, 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

Θ	Theta angle
<	Inferior
>	Superior
°C	Degree Celsius
%	Percent
µm	Micrometer
AFNOR	Association française de normalisation
Al_2O_3	Alumina
$Al_2Si_2O_5(OH)_4$	Kaolinite
As	Arsenic
B.E.T	Brunauer–Emmett–Teller
B1	Brick sample with 10% sludge
B2	Brick sample with 20% sludge
B3	Brick sample with 30% sludge
B3.5	Brick sample with 35% sludge
B4	Brick sample with 40% sludge
B5	Brick sample with 50% sludge
B6	Brick sample with 60% sludge
$CaCO_3$	Calcium carbonate
$CaMg(CO_3)_2$	Dolomite
CaO	Calcium oxide
Cd	Cadmium
CO_2	Carbon dioxide
COD	Chemical oxygen demand
BOD	Biochemical oxygen demand
Cr	Chromium
Cu	Copper
EDX	Energy dispersive X-ray
EN	European Norm
Fe_2O_3	Ferric oxide
g/cm^3	Gram per cubic centimeter
HCl	Hydrogen chloride
ICP-AES	Inductively coupled plasma atomic emission spectrometer
K_2O	Potassium oxide
KV	Kilovolt
L/S	Liquid/ solid

LL	Liquidity limit
Loi	Loss on ignition
mA	Milliampere
MgO	Magnesium oxide
Mg/L	Milligram per liter
mgO_2/L	Milligrams of oxygen per liter
mg/kg	Milligram per kilogram
$mm^3/year$	Cubic millimeter per year
m^3/day	Cubic meter per day
m^3/m	Cubic meter per meter
mm	Millimeter
ms/cm	Millisiemens per centimeter
m^2/g	Meter square per gram
Mn	Manganese
MnO_2	Manganese dioxide
MPa	Megapascal
Na_2O	Sodium oxide
Na_2CO_3	Sodium carbonate
NF-P	Norme Française - Bâtiment, génie civil
Ni	Nickel
Pb	Lead
PL	Plasticity limit
P_2O_5	Phosphorus pentoxide
pH	Potential of hydrogen
Pi	Plasticity index
SEM	Scanning electron microscopy
SiO_2	Silicon dioxide
SO_3	Sulfur trioxide
TFZ	Tangier Free Zone
TiO_2	Titanium dioxide
WWTP	Wastewater Treatment Plant
XRD	X-ray Diffraction
XRF	X-ray fluorescence
Zn	Zinc

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ORIGINAL RESEARCH ARTICLE

Cadmium and lead uptake by wild swamp eel in the populous river

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ABSTRACT

BACKGROUND AND OBJECTIVES: For enhanced environmental management of the Ciliwung River, toxic pollutions such as cadmium dan lead data are required. Cadmium and lead have widespread industrial applications. However, cadmium and lead are poisonous and classified as cancer-causing non-essential elements. Moreover, cadmium and lead accumulation in Ciliwung River-caught eels has not yet been examined. Consequently, it is essential to acquire the gathered data from this study. The primary objective of this study was to explore the accumulation of cadmium and lead in sediments and eel organs along the Ciliwung River and to estimate the weekly cadmium and lead intake from eel consumed by the people.

METHODS: Sediment and eel samples were collected at six sampling locations ranging from the upstream, midstream, and downstream regions. Method of 3051a of the United States Environmental Protection Agency was applied to analyze the metal yield from the sediment samples and targeted eel organs (gills, digestive tract, and flesh). In addition, quality control and quality assurance standards were employed, and Certified Reference Materials were used to ensure the quality of data and instruments.

FINDINGS: The average concentrations of cadmium (0.7825±0.3768 milligram per kilogram) and lead (36.9333±14.9040 milligram per kilogram) were greater than their natural levels. The average cadmium concentration in riverine sediment was below the interim sediment quality guidelines. However, the lead concentration exceeded the guidelines. The cadmium and lead accumulation patterns in the sediment and eels were found to be lowest in the upstream and found increased in the downstream are. In this case, the gills acquired the most concentration of cadmium (1.4571±0.3433 microgram per gram) and lead (43.2489±18.6775 microgram per gram). The fact that eel gills accumulated the highest cadmium and lead indicates the presence of heavy metals in their environment. The accumulation of cadmium and lead in the eel surpassed the permitted levels. According to the Provisional Tolerable Weekly Intake estimation, this research showed 0.0328 milligram/week for the cadmium and 1.2826 milligram/week for the lead.

CONCLUSION: The prevalence of cadmium and lead in riverine sediments and eels in the Ciliwung River is believed to be predominantly the result of inefficient wastewater management. However, cadmium and lead pollution must be handled with extreme caution because it interferes with the physiological processes of the biota, hence decreasing the population of eels and posing a health risk if consumed. In general, Asian swamp eels from the Ciliwung River are still edible. As a result, it is hoped that enhanced management will reduce the number of pollutants entering the riverine ecosystem.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
96	5	1

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INTRODUCTION

The river ecosystem is one of the most interactive ecosystems considering that it is affected by natural and human factors. As the commercial hub of an area developed, river is recognized as one of the earliest establishments of civilization. Rivers provide basic needs such as drinking and agricultural water sources, transportation, trade, recreational purposes, energy sources (hydroelectric), and other ecosystem service providers (Sulistyowati *et al.,* 2022). However, the proliferation of improperly managed human activities produces ecological stresses that surpass the river ecosystem's capacity for assimilation (Wijesiri *et al.,* 2018). In Indonesia, more than 50 percent (%) of the pollution status of rivers are polluted and heavily polluted (Statistic Indonesia, 2021). This motivates stakeholders to work toward a better river ecosystem management and ecological restoration. This compels stakeholders to enhance the river's environment in order to maintain and restore its ecological function (Riani *et al.,* 2018). The rehabilitation of the Ciliwung River, whose middle and downstream regions are in Jakarta, the Indonesian capital, is one of the government's top priorities (Pambudi, 2020). It is estimated that over 71,000 families and 350,000 individuals reside in the Ciliwung banks zone. Environmental management is not available to all residents of this region. For improved environmental management of the Ciliwung River, data pertaining to environmental contamination are required, particularly pertaining to heavy metals in riverine sediments and their accumulation in creatures inhabiting this ecosystem (Koesmawati *et al.,* 2018; Lestari *et al.,* 2018; Riani *et al.,* 2018). Heavy metal contamination is a type of water pollution that receives special consideration alarm (Islam *et al.,* 2015). Essential and non-essential types of heavy metals are distinguished (Riani *et al.,* 2014, 2018; Rosado *et al.,* 2016). In this case, iron (Fe) and zinc (Zn) are essential heavy metals that play a role in biological systems despite their harmful effects in high quantities (Mohammed *et al.,* 2011). On the other hand, non-essential heavy metals that are hazardous in low doses, such as cadmium (Cd) and lead (Pb), have no known biological role (Ali and Khan, 2019). In addition, the Agency for Toxic Substances and Disease Registry (ATSDR, 2012) considers both of these metals hazardous heavy metals in its classification system. Heavy metals have the potential to bioaccumulate in the body, and their levels have the potential to rise (biomagnify) as a result of the feeding process that occurs along the food chain (Saher and Siddiqui, 2019). To comprehend this, it is crucial to examine the accumulation and deposition of heavy metals in the geochemical phase in order to determine the possibility of bioavailable compounds linked to ecotoxicity threats (Dixit *et al.,* 2015). In addition, the degree of heavy metal pollutant pollution can be quantified more precisely by examining the accumulation of heavy metals in riverine sediment (Kaewtubtim *et al.,* 2016). Sediments play a crucial role in the transportation of contaminants, such as heavy metals (Miranda *et al.,* 2021). When the current pattern diminishes, the transport mechanism for redistributing polluted material frequently involves the transient adsorption of suspended particles, followed by releasing the polluting material to the surrounding environment (Custodio *et al.,* 2020). After sediment analysis, biomonitoring is essential to undertake additional environmental assessments about heavy metal pollution. Fish are frequently employed for biomonitoring and are one of the most informative aspects when studying pollution in aquatic environments (Yin *et al.,* 2012). Additionally, fish are also the most preferred biota for human consumption. The presence of contaminants, specifically heavy metals in fish, that people afterwards consume disrupts the metabolism or, in the worst case, is one of the causes of cancer (Riani, 2017). The Asian swamp eel (*Monopterus albus*) is a species of eel that inhabits Asian wetlands and riverbanks. Its organisms interacting directly with silt and murky water may accumulate heavy metals (Yin *et al.,* 2012). This kind of eel is highly popular in Indonesia as both a farmed and wild fish, notably those captured in the Ciliwung River. The Ciliwung River is contaminated with heavy metals, which increases the likelihood of heavy metal buildup in creatures that come into contact directly with the mud, such as eels. Sadly, this has not been investigated. Aksari *et al*. (2015), who examined the content of heavy metals (Cd, Hg, and Pb) in amazon sailfin catfish, are among the researchers who have conducted heavy metal accumulation investigations in Ciliwung (*Pterygoplichthys pardalis*). Furthermore, Ismi *et al*. (2019a) researched the ten types of heavy metals contained in the flesh of broom fish (*Pterygoplichthys pardalis*). Elfidasari *et al*. (2019)

investigated the pollution of Ciliwung water with heavy metals. Elfidasari *et al*. (2020) further also examined the concentration of heavy metals in water, sediment, and *Pterygoplichthys pardalis*. Meanwhile, Elfidasari *et al*. (2018) examined the connection between heavy metal concentration and nutritional content in Plecostomus (*Pterygoplichthys pardalis*). Ismi *et al*. (2019b) analyzed the heavy metal concentration of Plecostomus (Loricariidae). Putri *et al*. (2022) investigated the dangers of heavy metal (Cd, Hg, Pb) presence in processed *Pterygoplichthys pardalis* products to human health. In addition, Mulyaningsih *et al*. (2020) examined the heavy metals contamination in sediment, whereas Cadmium and lead uptake by wild swamp eel in the densely populated Ciliwung River that have never been evaluated. In this study, Cd and Pb were chosen because Riani *et al*. (2018) found significant amounts of Cd and Pb in Jakarta Bay, where the Ciliwung River drains, and it has been demonstrated to induce abnormalities in green mussels. In addition, operations in the Ciliwung watershed, such as the battery and electroplating industries and the use of natural phosphate rock-based fertilizers in agricultural activities upstream to the middle of the Ciliwung River, can produce Cd-containing trash. Transportation in the middle and downstream portions of the Ciliwung watershed is likewise classified as high to very high, even though transportation activities and various types of industries in the middle and downstream regions have the potential to generate relatively high levels of pollutants. Therefore, Cd and Pb were chosen for this investigation due to their significant potential for contamination of the Ciliwung River. Based on this information, it is essential to investigate the uptake of Cd and Pb heavy metals in riverine sediments and wild Asian swamp eels inhabiting the Ciliwung River. The findings of this study will be necessary for the environmental management, particularly in determining the fate of Cd and Pb in the riverine ecosystem. The aims of this primary was to investigate the accumulation of Cd and Pb in the river sediments and eel organs from upstream to downstream of the Ciliwung River and to estimate the weekly intake of Cd and Pb from eel consumed by the local community. Therefore, this study was undertaken on the Ciliwung River in Indonesia during the dry season of 2022.

MATERIALS AND METHODS

Study area description

The Ciliwung River drains an area of more than 476-kilometer square (km^2) with length of the river of 119 kilometer (km). This river flows through the administrative territory of three provinces: West Java Province (Bogor Regency, Bogor City, Depok City), DKI Jakarta Province (South Jakarta City, East Jakarta City, Central Jakarta City, West Jakarta City, and North Jakarta City), and Banten Province (Tangerang City and Tangerang Regency). The Ciliwung River serves as a source of water for fisheries, agricultural, and industrial activities in the upstream region and a source of potable water in the upstream and midstream areas. Mount Pangrango, at an elevation of 3,020 meters (m) above sea level, is the origin of the river. The annual precipitation range for the Ciliwung watershed is between 1,500- and 3,500-millimeter (mm). The province of DKI Jakarta has the greatest portion of the Ciliwung Watershed, including 40% of its total area. Land use features in a river's upstream, midstream, and downstream are incredibly distinct. In the upstream land use, there is a mixture of primary forest, agricultural land, and settlements; however, in the midstream and downstream, practically all of the area is built-up land. In the Ciliwung watershed, there has been a considerable shift in land cover, particularly the replacement of agricultural and forest areas with built-up land, which has increased by more than 100% annually since 1990 (Abighail *et al.,* 2022). So that the hypothesis in this study are the concentrations of Cd and Pb in the river sediment is higher than their natural levels, Cd and Pb accumulation at riverine sediments and target organ eels increase from upstream to downstream, and the accumulation of Cd and Pb in the eel is greater than in the sediment.

Field sampling

The sampling technique was applied at six locations (Fig. 1). The two stations represent the upstream area (CL01-CL02), midstream area (CL03-CL04), and downstream area (CL05-CL06), respectively. Three sediment samples were collected at each sampling location using a sediment grab from the river's middle and from each embankment (van Veen grab sampler). On the surface of the sample in the

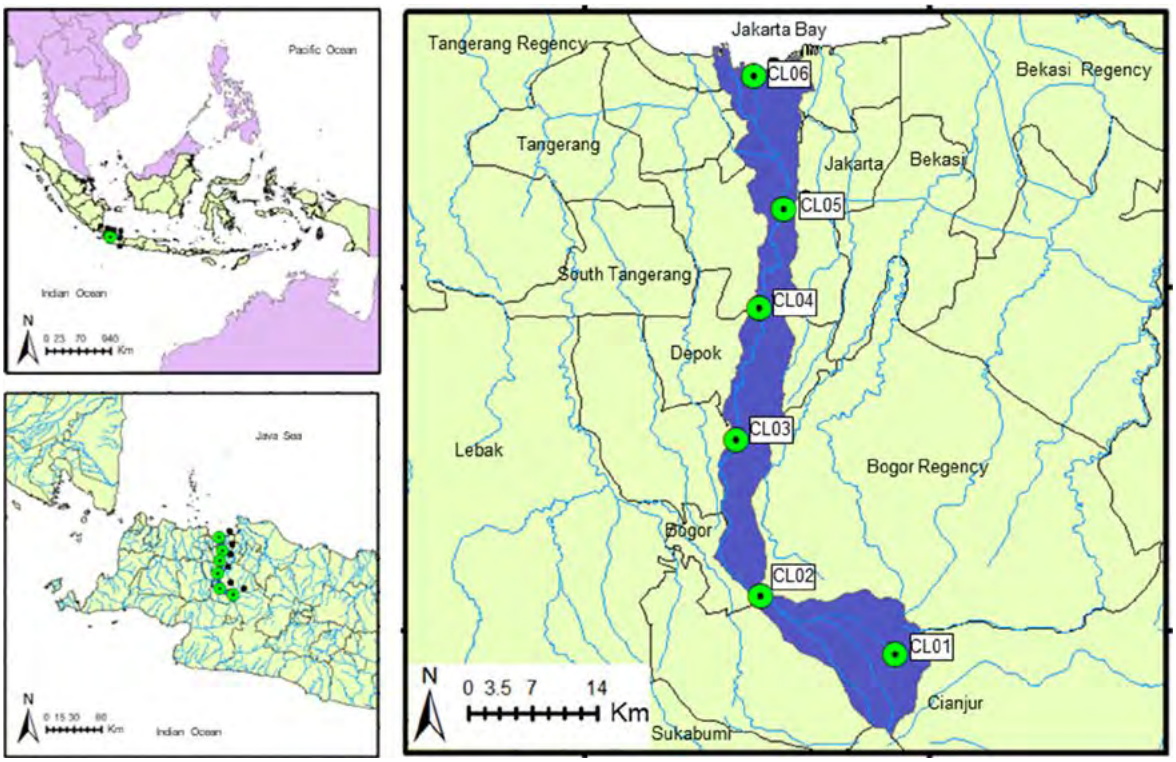

Fig. 1: Geographic location of the study area along with the sampling locations at Ciliwung River, Indonesia

sediment grab (about 10 to 15 centimeters (cm)), a composite sample was obtained by homogenizing the sample using a plastic spoon. The sample was then placed in a 300-milliliter (mL) glass container. Specimens of the Asian swamp eel were collected with the assistance of local fishermen by fishing for the eel in its nest on the bank of the Ciliwung River. The length and weight of the eels captured were determined. The length of eels varied from 11.86 to 42.02 centimeter (cm), with a mean of 27.06 cm. The average weight of the obtained eels was 13.46 gram (g), with a range of 4.2 to 25 g. Asian swamp eel samples were further put in a glass container like sediment samples. For the analysis, all sediment samples and Asian swamp eels were placed in a cooler at a temperature of 4±2 degrees Celsius (°C).

Heavy metals analysis

Method 3051a of the United States Environmental Protection Agency (USEPA, 2007) was used to analyze the metal yield from the sediment and eel samples. In this case, surgical equipment was used to dissect each individual eel. On separate sheets of sterile aluminum foil, the eel's gills, digestive tract, and flesh, as well as the sediment, were placed. Samples of sediment and eels were then dried for 24 hours at 105°C to eliminate water content (Cordova *et al.,* 2017). After the drying, the sample was finely powdered in a mortar. In test tubes containing samples, 3 mL of hydrochloric acid (HCl) and 9 mL of nitric acid (HNO_3) were added to transform organometallic into inorganic form (Riani *et al.,* 2018). The sample was then placed in the Microwave Accelerated Reaction System (MARS) microwave digestive oven (CEM MARS5 Xpress) for 15 minutes at 185°C. The sample was let to rest for 30 minutes before being diluted with 25 mL of ultrapure water. All samples were further evaluated using the Thermo Scientific iCAP 7400 Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) for Cd and Pb levels. This research also employed quality control and quality assurance (QC/QA) to guarantee that all processes were adequate and well-managed (Harmesa and

Cordova, 2020). As samples, the National Research Council of Canada Certified Reference Materials (CRM) DOLT-5 (for trace metals) and PACS-3 (for sediments) were utilized. All CRM test results fall within the certificate's specified range (NRCC, 2013; NRCC, 2014).

Data analysis

For the Cd and Pb content in sediments, data analysis in this study is reported in milligram per kilogram (mg/kg), whereas the level of Cd and Pb in eels is shown in microgram per gram (µg/g). The initial analysis compared the Cd and Pb concentrations in riverine sediment to the Canadian Council of Ministers of the Environment (CCME, 2001) sediment quality guidelines and natural concentrations. In contrast, eels' Cd and Pb concentrations were compared to the Food and Agriculture Organization/World Health Organization of the United Nations (FAO/WHO 2019) permissible levels. This study's statistical analysis, which comprised descriptive statistics (mean and standard deviation of Cd and Pb) and a significant difference test utilizing a non-parametric test (the Kruskal-Wallis test followed by the Mann-Whitney post hoc test), was conducted using PAST Software Version 4.03.

RESULTS AND DISCUSSION

Cd and Pb concentrations in sediments and eels from Ciliwung river

Ciliwung River is a river that receives a significant amount of waste runoff from human activities. Industrial, residential, agricultural, urban, and other anthropogenic activities exist near the river and dump their waste into the waterway. On the other hand, anthropogenic activities such as wastewater disposal from industrial and domestic activities, smelting in mining activities, burning fossil fuels, and use of fertilizers and pesticides in agricultural activities are anthropogenic sources of heavy metals such as Cd and Pb (Yousif *et al*., 2021), which enter the water and eventually settle and become trapped in the sediment (Fretes *et al*., 2020, Riba *et al*., 2004). In contrast, eels as infauna in the Ciliwung River that inhabit sediments contaminated with Cd and Pb will get contaminated with Cd and Pb. Fig. 2 demonstrates the typical Cd and Pb concentrations in the sediments and eel target organs. The average Cd concentration (0.7825±0.3768 mg/kg, in riverine sediment (Fig. 2a) in Ciliwung was relatively lower than the interim sediment quality guidelines of CCME (2001). However, the Pb concentration (36.9333±14.9040 mg/kg) was higher (Fig. 2b). Furthermore, the average levels of Cd and Pb were higher than in natural concentrations which were 0.102 mg/kg (Cd) and 17 mg/kg (Pb), respectively (Wedepohl 1994). The average content of Cd and Pb in Ciliwung River sediments was slightly less than the XRF results of Elfidasari *et al*. (2020). The concentrations of Cd and Pb in the Ciliwung river were lower than rivers in China (Li W *et al.,* 2022; Li X *et al.,* 2022; Fang *et al.,* 2022), India (Saikia *et al.,* 2022), Pakistan (Hossain *et al.,* 2021), and Mexico (Vargas-Solano *et al.,* 2022), comparable to those in Argentina (Magni *et al.,* 2021), Poland (Jaskuła and Sojka, 2022), and Thailand (Ta and Babel, 2020), as well as greater than those in Zambia (Nakayama *et al.,* 2010) and Iran (Jafarzadeh *et al.,* 2020). Compared to FAO/WHO (2019) permissible levels (2 µg/g for Cd and Pb), the accumulation of Cd (0.7808±0.5339 microgram per gram (µg/g) in eels is comparatively moderate (Fig. 2c). However, the accumulation of Pb (30.5384±15.3307 µg/g) in eels greatly surpassed these levels (Fig. 2d). The amount of Cd and Pb in eels was much higher than in the flesh of *Pterygoplichthys pardalis* caught in the Ciliwung River and analyzed by XRF with concentrations of Cd 0.2-0.4 µg/g and Pb 1.9-2.88 µg/g (Elfidasari *et al*., 2020) and much higher than the amount of Cd and Pb allowed in fish flesh by several permissible standard limit (BPOM, 2018; FAO/WHO, 2011; SNI, 2009; CFDA, 2017; European Commission, 2006; Canada Guidelines, 2018; ANZFS, 2016) (Table 1). The much higher bioaccumulation in eels was considered to be because eels are aquatic biota that lives in mud, which is rich in organic matter, so it will accumulate (or "trap") heavy metals much more than biota that lives in the water column and sand and rock sediments (Riani *et al*., 2017). This fits with what Fretes *et al*. (2020) said about sediment being a place where heavy metals can be absorbed. Heavy metals in the water column will go through a deposition process and build up in sediments, and then they will build up in the bodies of benthic organisms. Pb presented in greater amount in sediments and eels than Cd in each sampling station. The gill was the organ that accumulated the

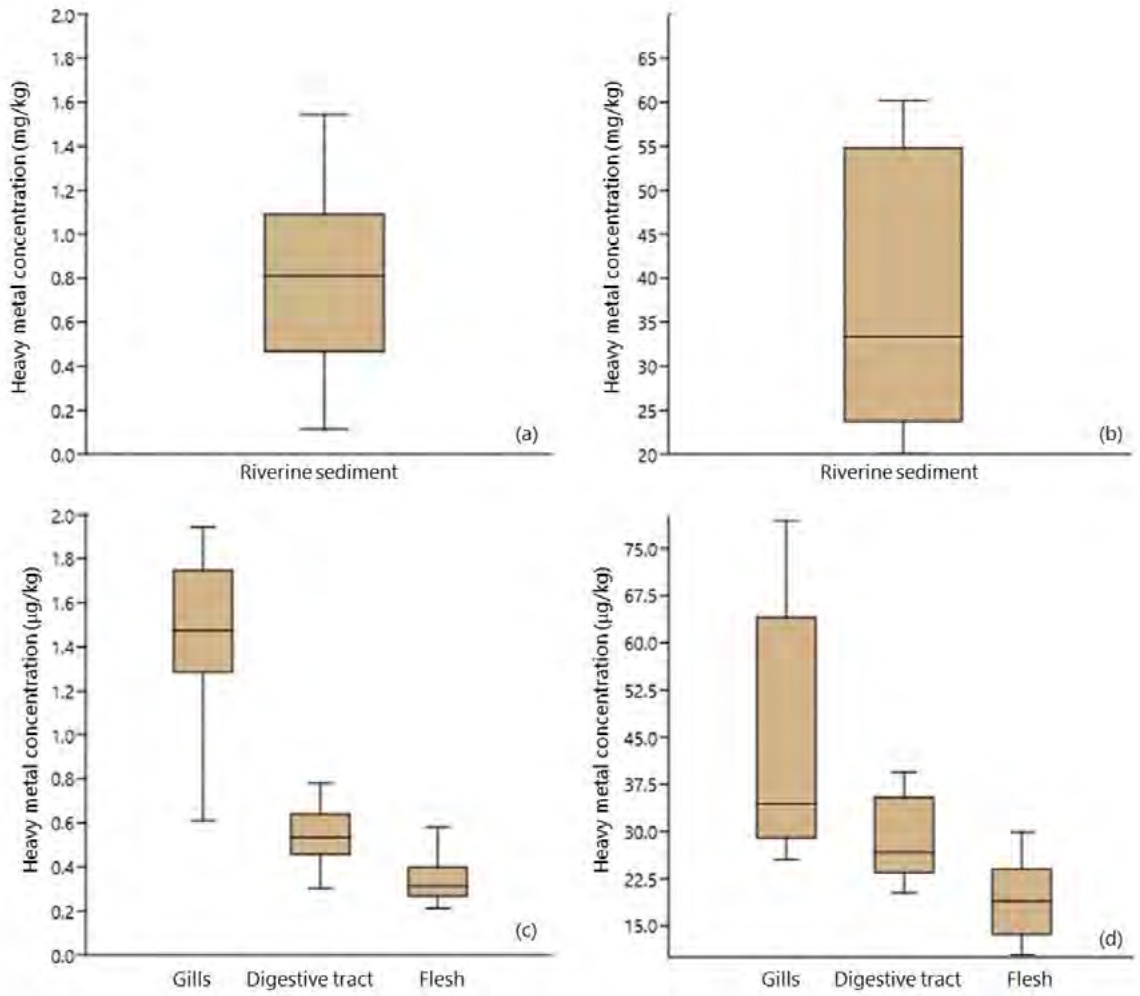

Fig. 2: The concentrations of Cd in the sediments (a), Pb in the sediments (b), Cd in the eels targeted organ (c), and Pb in the eels targeted organ (d)

Table 1: Concentrations of Cd and Pb in Ciliwung River eels compared to several permissible standard limit

Heavy metals	Concentration in eels from Ciliwung River (µg/g)	BPOM, 2018	FAO/WHO, 2011	SNI, 2009	CFDA, 2017	European Commission, 2006	Canada Guidelines, 2018	ANZFS, 2016
Pb	30.5384±15.3307	0.2	0.03	0.3	0.2	0.3	0.5	0.5
Cd	0.7808±0.5339	0.1	0.01	0.1	0.05	0.05	-	-

most Cd and Pb in eels, followed by the digestive tract. Compared to the other two organs, the flesh had the least amount of Cd and Pb. The gills of eels accumulated the most Cd and Pb, indicating the heavy metal content in their environment (water and sediment). Asian swamp eels inhabit shallow, murky waters with a mud-to-water ratio of 80:20 (Nhan *et al.,* 2019). Gill is the first organ in contact with the environment and serves as a site for ion absorption from the surrounding environment (Heath, 2018).

Heavy metals that exist in the environment and enter the gills are bound, transported, and stored by gill cells (Luo *et al.,* 2014). Then, the gill cells control the balance between oxidation and reduction to control the stress response to heavy metals (Luo *et al.,* 2014). In accordance with several earlier studies on the same or similar fish species, this investigation discovered distinct heavy metal accumulations in different organs. Similar to studies conducted in Turkey (Karadede *et al.,* 2004), Malaysia (Yin *et al.,* 2012), and France (Oliveira Ribeiro *et al.,* 2005), heavy metal accumulation in benthic fish was the highest in the gills and lowest in other organs. Meanwhile, the flesh acquired the lowest accumulation of heavy metals because it is a relatively inert organ in the process of interacting with the environment (Roméo *et al.,* 1999).

Heavy metals originate from both natural and anthropogenic sources, including rock weathering, volcanic activity, and atmospheric deposition, as well as residential, agricultural, and industrial activities (Fang *et al.,* 2016a; Harmesa *et al.,* 2020; Suresh *et al.,* 2012). In this research, the influence of human-made sources was greater than that of natural sources. According to Hosono *et al*. (2011), heavy metals started to accumulate in Jakarta Bay, the estuary of the Ciliwung River, from the 1920s to the 1990s (due to the industrialization) and then commenced to decrease in the 2000s (owing to the increased stringency of environmental restrictions). The two heavy metals examined in this study are believed to originate from human activity. Cd is utilized as a raw material in the battery and electroplating industries (Harmesa and Cordova, 2020). In addition, Cd is a heavy metal present in natural phosphate rock-based fertilizers that are bonded to Cd (Ayangbenro and Babalola, 2017; Liu *et al.,* 2016; Tang *et al.,* 2010). Consequently, Cd is typically observed in agricultural areas. The Ciliwung watershed region, particularly upstream, remains an agricultural region. Based on what this study found, more research projects should be done on the amount of heavy metals in agricultural fertilizers in the Ciliwung watershed. The relationship between Pb accumulation and transport activity is strong (Burton *et al.,* 2005). It is associated with heavy land, sea, and air transportation activities that lead-containing fuel enters the combustion engine system and is expelled in the exhaust (Hossain *et al.,* 2019; Sakawi *et al.,* 2013). In addition, Pb is also produced through industrial processes. The amount of Pb in the environment goes up as the number of industrial operations goes up (Liu *et al.,* 2016; Tepanosyan *et al.,* 2017).

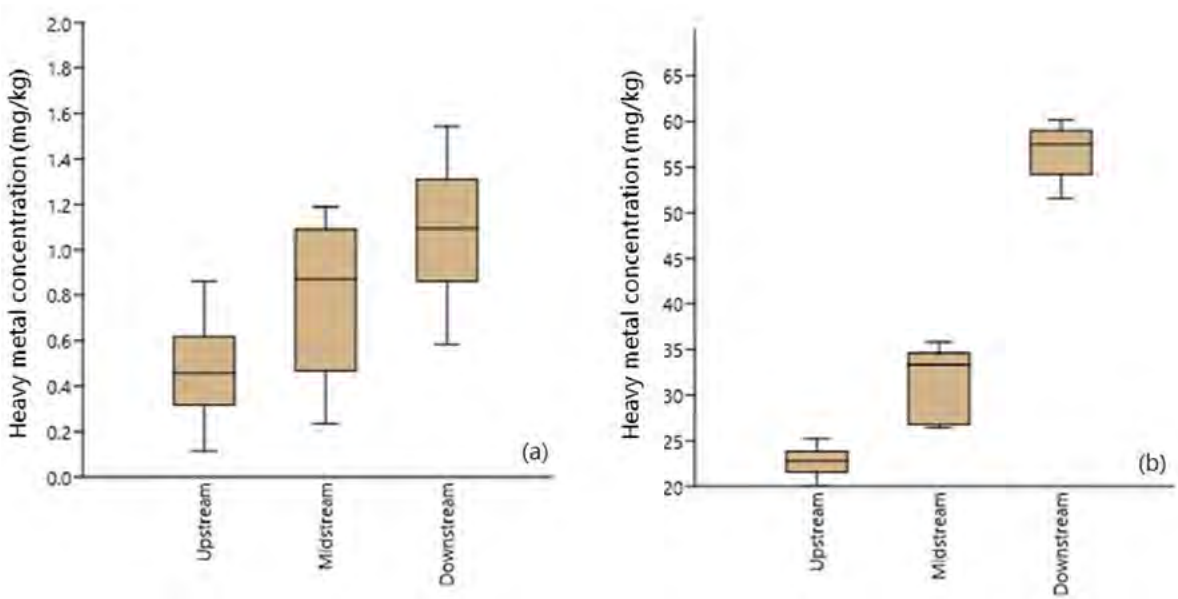

Fig. 3: Spatial distribution of Cd (a) and Pb (b) in riverine sediment from Ciliwung River

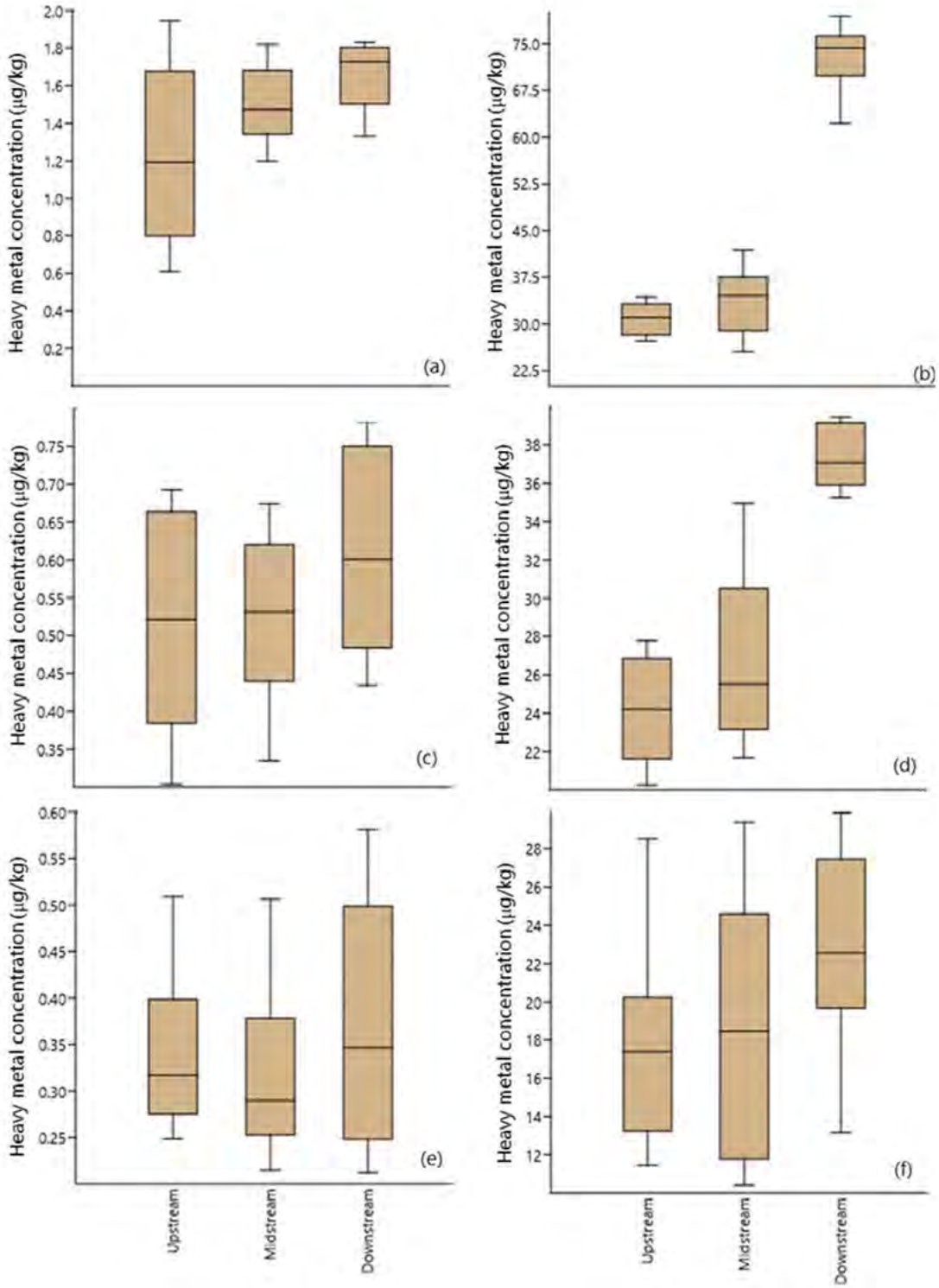

Fig. 4: Spatial distribution of Cd in gill (a), digestive tract (c) and flesh (e) and Pb in gill (b), digestive tract (d) and flesh (f) from Ciliwung River.

Spatial distribution of Cd and Pb in sediment and target organ eels from Ciliwung River

The findings of the study of Cd and Pb in sediments and eels from the upstream, midstream, and downstream regions of the Ciliwung River are presented in Fig. 3 and Fig. 4. The Cd and Pb accumulation pattern in the two research objects were found to be lowest in the upstream area and continue to increase in the downstream area. There were significant differences in sediments ($p<0.05$) for Pb accumulation in the upstream, midstream, and downstream regions (Fig. 3a), whereas only in the downstream and upstream regions for Cd accumulation (Fig. 3b). Variations in the accumulation of Cd and Pb in target organs of the eel were induced by differences in the accumulation of Cd and Pb in upstream, midstream, and downstream sediments. This study demonstrated substantial variance in the accumulation of Cd in the gills (Fig. 4a) and digestive system (Fig. 4c) of upstream eels. However, variation in the accumulation of Cd in the flesh was higher in the downstream region (Fig. 4e). Different things were discovered in the variation of Pb accumulation that was not readily apparent in the gill (Fig. 4b) and digestive tract (Fig. 4d). However, there was a significant variation of Pb accumulation in the flesh in the midstream region (Fig. 4f).

On the rationale of additional analysis, there were significant differences ($p<0.05$) between the upstream and midstream regions and the downstream regions for Pb accumulation solely in the gill and digestive organs. At the same time, there were no significant differences in the target organs for Cd accumulation. Heavy metals arising from natural processes and human waste that are not effectively managed will enter water bodies and be transported by freshwater flows (Fang *et al.,* 2016b). The water flow in the upstream region of the Ciliwung River originates from Mount Gede Pangrango, a volcano with an active status but at a normal level. The accumulation of heavy metals in riverine sediments, which will eventually accumulate in the eel, is a natural consequence of rock weathering, erosion, and volcanic activity (Hussein *et al.,* 2021; Wuana and Okieimen, 2011). In addition, the source of heavy metals in upstream regions is the result of human activities, particularly agriculture and domestic activities with inefficient wastewater treatment. This study's findings show that the concentration of Cd and Pb tends to grow in the likely midstream result of domestic and industrial activities. These human-based activities happened more often in the upstream area, which made the pattern of Cd and Pb buildup more prominent (Harmesa and Cordova, 2020; Thongyuan *et al.,* 2021). On the other hand, Cd and Pb are heavy metals that can induce toxic effects that can affect biota in aquatic environments (Sanchez, 2014). In addition to being hazardous, heavy metals also harm the ecosystem due to their toxicity, solubility, and ability to accumulate in organisms (Demkova *et al.,* 2017). Cd and Pb that have settled in the sediment will be acquired by creatures (particularly benthic organisms) by diffusion through the skin, digestion, and osmoregulation (Riani, 2017). In addition, metals that cannot be detoxified and expelled will bind to enzymes, causing them to accumulate and disturb numerous systems and physiological organisms of the organism (Riani *et al.,* 2017). Therefore, heavy metals, particularly Cd and Pb, can have a significant effect even in small amounts (Wuana and Okieimen, 2011); thus, it is essential to consider this condition. Cd and Pb can be transported from upstream to downstream and into estuaries and marine ecosystems by water currents (Fernández-Cadena *et al.,* 2014), transporting Cd and Pb adsorbed by suspended solids (González-Ortegón *et al.,* 2019). Heavy metals contained in river sediments will undergo an anaerobic decomposition process that promotes movement between locations and is highly prone to enter the organs of biota (Demirbilek *et al.,* 2013), such as eels whose nests are located in river mud. The higher organic content and comparatively low oxygen level of river mud (Hussein *et al.,* 2021) generate methanogenic conditions (Ishchenko, 2019) that make it easier for reductive metals to be released (Thongyuan *et al.,* 2021) and enter the eel's organ (Li *et al.,* 2009). The gill is the organ with the highest concentration of heavy metals, particularly in the downstream region. This is because the gill interacts directly with the mud and suspended particulates and the greater concentrations of Cd and Pb in the downstream region. In addition, the bioavailability of Cd and Pb will multiply in mud and suspended particles (Bergamaschi *et al.,* 2012). This study was conducted during the dry season when there is substantially less natural water compared to greywater from human activities. As a result,

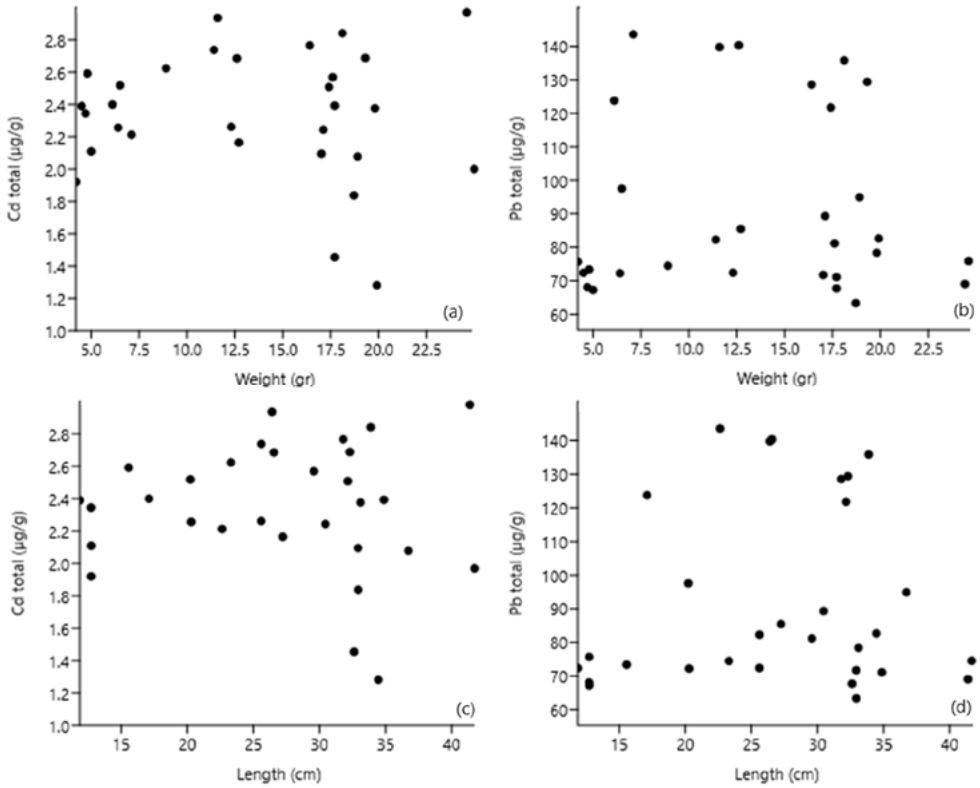

Fig. 5: Correlation between eel weight and total Cd (a), eel weight and total Pb (b), eel length and total Cd (c), and total eel and Pb length (d)

heavy metal transport mechanisms can increase and tend to be deposited more in river sediments (Wijesiri *et al.,* 2018). The increasing concentrations of Cd and Pb from upstream to downstream, both in sediments and those accumulated in the body of the eel, are considered to be linked to the vastly different land uses in the upstream, middle, and downstream rivers. In the upstream area, the land is dominated by primary forest, agricultural land, and a small number of settlements, whereas further downstream, almost the entire area is built-up land (Abighail *et al*., 2022). Aside from this, field observations reveal that there are significantly fewer upstream activities, with only a few domestic and agricultural activities, but downstream activities are more diverse and numerous and even more dominated by industrial, transportation, and urban activities. Consequently, the concentration of lead is rising downstream. Cd and Pb created in the upstream area will also be carried downstream by river currents (Fernández-Cadena *et al*., 2014).

This study found a correlation between the length and weight of an eel's body and the overall accumulation of Cd and Pb in the gill, digestive tract, and flesh. The correlation results are displayed in Fig. 5. All relationships between eel weight and total Cd (Fig. 5a), total eel weight and Pb (Fig. 5b), total eel length and Cd (Fig. 5c), and total eel length and Pb (Fig. 5d) follow the same pattern. R-squared (R^2) is the proportion of the variation of a dependent variable that an independent variable or variables can explain in a regression model. The investigation revealed a very modest connection (R^2<0.1) between the body size of wild eels and the accumulation of Cd and Pb. This result showed that a connection between metal uptake from contaminated ecosystems might vary. It might be due to ecological demands, metabolism, contamination gradients in water, food, and sediment, as well as other parameters such as salinity, temperature, and interacting agents (Pagenkopf,

Table 2: The estimated weekly intake of Cd and Pb from eel flesh and whole eel

Eel body part	Region area	Estimated weekly intake (mg/week)	
		Cd	Pb
Eel flesh	All region	0.0143	0.8191
	Upstream	0.0144	0.7326
	Midstream	0.0136	0.7956
	Downstream	0.0156	0.9547
Whole eel	All region	0.0328	1.2826
	Upstream	0.0291	1.0108
	Midstream	0.0329	1.1151
	Downstream	0.0368	1.8606
Maximum weekly intake (MWI) mg/week		0.39-0.43	1.41-1.54

1983; Custodio *et al.,* 2020; Yin *et al.,* 2012).

Eels are one of the most popular types of fish and are even sought after by Indonesians; for example, in 2010, Jakarta alone required 20 tons of eels per day, Yogyakarta required 30 tons of eels per day, and various other cities required the same amount (Warta Pasar Ikan, 2010), thus eels have even become a commodity. The strong demand for eels from within the country is due to the low-fat content and the presence of the essential unsaturated fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). The results of a survey of residents of the Ciliwung watershed indicate that a significant number of people are searching for eels in the Ciliwung River for consumption by their families. Given that eels from the Ciliwung River are contaminated with high levels of Cd and Pb, their intake must be restricted so as not to put consumers at risk. The estimated weekly intake of Cd and Pb from eel flesh and whole eel is presented in Table 2. According to the findings of the analysis, the estimated average accumulation of Cd and Pb in eel flesh was 0.0143 mg/week and 0.8191 mg/week, respectively, while the corresponding values for whole eels were 0.0328 mg/week (Cd) and 1.2826 mg/week (Pb). As with sediment accumulation and the eel's targeted organ, the estimated weekly intake of Cd and Pb tends to increase from upstream to downstream as the distance increases. The estimation results were then compared to the Maximum Weekly Intake (MWI) derived from the average weight of Indonesian women (56.2 kg) and men (61.4 kg) and the Provisional Tolerable Weekly Intake (PTWI) from FAO/WHO (2019) of 7 g/ kg and 25 g/ kg for Cd and Pb, respectively. The estimated weekly intake of Cd and Pb was lower than the MWI, except for the estimated weekly intake of Pb from entire eels in the downstream area (1.8606 mg/ week). In general, eel from upstream, midstream, and downstream is still acceptable for consumption; nevertheless, consumers must continue to monitor the eel's Pb intake, particularly in the downstream area. An excessive Pb dosage can interfere with metabolism, limit growth, and diminish survival rates (Burton *et al.,* 2005; Tepanosyan *et al.,* 2017). Heavy metals will negatively affect numerous body organs, causing cellular disruptions at the molecular level and influencing the glycolysis, Krebs cycle, and lipid metabolism in organism cells (Strydom *et al*., 2007). Even non-essential heavy metals such as Cd and Pb exhibit substantial toxicity at low concentrations (Okoro *et al*., 2012). Their bioaccumulative qualities cause heavy metal concentrations in live creatures to increase with time (Naser, 2013), increasing Cd and Pb pollution. Particular consideration should be given to the population's regularly consumed eels. Long-term exposure to Cd and Pb increases the chance of developing high blood pressure, renal illness, cardiovascular disease, and impaired fertility in the reproductive organs (David and Isangedighi, 2019). In addition, heavy metals Cd and Pb that accumulate in fish can also damage the health of humans who consume them due to the toxicity of Cd and Pb, which can lead to kidney, hypertension, liver, and pulmonary illnesses, among others (Sonone

et al., 2020; Abu-Qdais *et al.,* 2020). The buildup of Cd and Pb in fish can have cytotoxic, genotoxic, and mutagenic consequences (Matos *et al*., 2017), therefore if humans ingest eels polluted with high levels of Cd and Pb, they may experience the same side effects. Even though the Cd concentration in the Ciliwung River sediment was still below the sediment quality guidelines from CCME (2001), the average concentration of Cd and Pb is higher than the natural concentration. It has accumulated in the eel, causing ecosystem damage and physiological disturbances in the eels and danger to humans who consume them. Therefore, comprehensive management must be conducted following the nature of the Indonesian people, namely management based on zero waste technology, blue economy, and law enforcement, in order to minimize the input of Cd and Pb into rivers and bring economic benefits, while also combining monitoring and evaluation with strict law enforcement on the ground.

CONCLUSIONS

This study studies the deposition of Cd and Pb in the sediments and eels of the Ciliwung River from upstream to downstream. Based on the analysis results, it was determined that the concentrations of Cd and Pb in the river silt are higher than their natural levels. Cd and Pb concentrations in the Ciliwung River sediments are higher than their natural values relative to the interim sediment guidelines, although only Pb concentrations are above the threshold. Cd and Pb are bioaccumulated by eels, whose habitat is sediments. The buildup of Cd and Pb increase from upstream to downstream, both in the sediment and in the internal organs of the eel. Cd and Pb concentrations are higher in the eel than in the sediment. The amounts of mercury and lead are also higher in the gills compared to the digestive system and the flesh. The eel exceeds FAO/WHO permitted values for Cd and Pb accumulation. The correlation analysis between the body of the eels in terms of length and weight to be connected with the accumulation of lead and cadmium in the gill, digestive system, and flesh yielded data indicate a very weak correlation between the three variables. This research demonstrates the disparities in ecological requirements, metabolic rates, and contamination gradients that each organism of eel encounters in its water, food, and sediment environments. Nevertheless, according to the estimation of the Provisional Tolerable Weekly Intake, eels from the Ciliwung River can be consumed within strict limitations and in small quantities, hence preventing exposure to Cd and Pb accumulated by eels. It is believed that the presence of Cd and Pb in riverine sediments and eels in the Ciliwung River is primarily due to improper wastewater disposal from human activities. Consequently, it is anticipated that improved management will decrease the number of pollutants entering the riverine ecosystem based on zero-waste technologies, blue economy principal, and stringent law enforcement.

AUTHOR CONTRIBUTIONS

N. Nurhasanah, the corresponding author, has contributed in interpreted the results, and preparing the manuscript. L. Sulistyowati designed the field sampling and performed data analysis. E. Riani contributed to the data analysis and interpretation of the results. M.R. Cordova contributed to supervision, study design, laboratory analysis, data analysis, and writing with the assistance of the other authors. M. R. Cordova is the main contributor to this 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

ANZFS	Australia New Zealand Food Standards Code
ATSDR	Agency for Toxic Substances and Disease Registry
BPOM	Badan Pengawas Obat dan Makanan – Republik Indonesia (The National Agency of Drug and Food Control – Republic of Indonesia)
°C	degree Celsius
CCME	Canadian Council of Ministers of the Environment
CFDA	China Food and Drug Administration
Cd	Cadmium
Cm	Centimeter
CRM	Certified reference material
HCl	Hydrogen chloride (Hydrochloric acid)
HNO_3	Nitric acid
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectrometry
FAO/WHO	Food and Agriculture Organization/ World Health Organization of the United Nations
Fe	Iron
g	gram
ISQG	Interim sediment quality guidelines
kg	Kilogram
km	Kilometer
km^2	Kilometer square
m	Meter
MARS	Microwave accelerated reaction system
µg/g	microgram per gram
mg/kg	milligram per kilogram
mm	Millimeter
mL	milliliter
MWI	Maximum weekly intake
Pb	Lead
PTWI	Provisional tolerable weekly intake
R^2	R-squared
SNI	Standar Nasional Indonesia (Indonesian National Standard)
USEPA	United States Environmental Protection Agency
QC/QA	Quality control and quality assurance
Zn	Zinc

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ORIGINAL RESEARCH PAPER

Modeling the tropical fish community related to land uses and environmental determinants

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ABSTRACT

BACKGROUND AND OBJECTIVES: Coastal ecosystems worldwide have been threatened by changing land use and environmental determinants. These conditions have impacted important marine resources, including fish diversity. Southeast Asia, one region experiencing massive land use change, still has limited information on how land use and disturbed coastal ecosystems impact fish diversity. This information is urgently needed as fish is one of the most important food resources here. This study aims to assess and compare the environment and tropical fish community between disturbed and intact sites, represented by coasts dominated by settlements and coasts dominated by mangrove forests in West Java, Indonesia.
METHODS: Fish sampling was carried out at two sites: Jakarta as the disturbed site and Subang as the intact site; water quality was also measured at these sites. Land uses at the sites were interpreted using satellite imagery. Fish diversity was determined using the Shannon–Wiener index, rarefaction curve, and Lorenz graph. Principal component analysis, analysis of variance, and the x2-test were used to determine environmental factors that affected the fish community at both sites. Akaike's information criterion was assigned to model the relationship between environmental factors and the fish community.
FINDINGS: Coasts characterized by anthropogenic disturbances and the absence of mangrove cover have a lower potential of hydrogen (pH) and reduced fish diversity by up to 53.91%. The intact site had higher fish diversity and made a greater contribution to conservation by providing habitats for fish species with the least concern and vulnerability statuses, according to the International Union for Conservation of Nature Red List. From the AIC model, the decreasing water pH (AICc = 27.28) was the main determinant that reduces fish diversity at disturbed sites compared to dissolved oxygen (Akaike's information criterion = 28.13) and salinity (Akaike's information criterion = 29.95).
CONCLUSION: The coastal fish community was affected by differences in environmental factors, land uses, and mangrove cover driven by anthropogenic influences. The AIC model proved capable of assessing the effects of environmental factors on coastal fish communities. This study modeled environmental factors that should be managed and prioritized to restore and conserve the fish community along tropical coasts.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
71	9	4

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INTRODUCTION

Marine ecosystems, including coastal ecosystems, are subjected to several anthropogenic activities. The loss of coastal biodiversity has become a well-recognized feature of the Anthropocene. Anthropogenic disturbances caused by activities such as agriculture, massive urbanization, deforestation, and introduction of non-native species may contribute to the diversity of fish species within a community, for example, the reduction in fish diversity and the increased similarity in composition of fish species (Dornelas *et al*., 2014; Socolar *et al*., 2016). The disturbance induced by human activities in an intact ecosystem can promote the replacement of many endemic species with cosmopolitan fish (Li *et al*., 2018). Environmental disturbances related to anthropogenic activities include small farms, tourism, and fishing fleets (Méndez, 2021). Anthropogenic activities have been widely reported to have negative impacts on coastal ecosystems from the tropics to Antarctica. Even in remote places like Antarctica, the disturbed area along the coast showed lower values of biodiversity and taxonomic distinctness (Stark *et al.*, 2014), because of anthropogenic activities and disturbances in the form of old waste disposal sites, environmental pollution, and organic enrichment. Palacios-Sánchez *et al*. (2019) confirmed that the presence of anthropogenic impacts reduced salinity, fish abundance, and biodiversity values, as observed in the disturbed coasts receiving medium to high impacts. Nevertheless, the category of coasts without impacts has high values of fish diversity and abundance, and salinity, but low concentrations of nitrites, nitrates, and ammonia. In seagrass ecosystems (Iacarella *et al.*, 2018) near the coast, associated with high anthropogenic disturbance, the fish composition exhibits biotic homogenization. A site with this high disturbance was reported to have lower biodiversity than an area with low disturbance (Fakhry *et al*., 2020). The Southeast Asian region is known for its vast and lucrative tropical coasts that have high fish diversity. In this region, coastal ecosystems located on the West Java coast are known to have high fish species biodiversity, which include families of Leiognathidae (*Leiognathus* spp.), Sciaenidae, Synodontidae (*Saurida tumbil*), Bothidae, Ariidae (*Netuma thalassina*), Plotosidae, Nemipteridae (*Nemipterus hexodon*), Clupeidae, and Haemulidae (Partasasmita *et al*., 2015). However, this coast has been recently threatened (Nuryanto *et al.,* 2021) and disturbed by the presence of anthropogenic influences and land-use conversion from intact mangrove forests to human settlements (Fabinyi *et al*., 2022). In Indonesia, comparative studies on the fish community in both protected and disturbed environments are still lacking; however, this information is urgently needed as fish communities are threatened by the magnitude of anthropogenic activities on coasts. Currently, the West Java coast is threatened by population density and anthropogenic activities that have led to land-use change, reduced carrying capacity, and increased impacts on environmental quality (Handayani *et al*., 2017). The West Java coast has a population of 35 million, and this keeps increasing. This makes it the second largest urban population in the world (Octifanny and Hudalah, 2017) and can pose a significant threat to coastal fish resources. Considering this situation, this study attempts to address the following questions: are there any differences in the fish community between coasts disturbed by anthropogenic activity and intact coasts? If there is a difference, what are the primary environmental determinants affecting the fish community? The assessment was based on Akaike's information criterion (AIC) modeling as this method can select environmental factors that should be managed and prioritized to restore and conserve the fish community along disturbance gradients. Assessment and modeling results can then be applied to strategize the management and conservation of coastal fish, especially in controlling anthropogenic activities and regulating environmental factors related to those activities. The objectives of this study are to assess and compare the environment and tropical fish community between disturbed and intact sites, represented by disturbed coasts dominated by settlements (Jakarta coast) and intact coasts dominated by mangrove forests (Subang coast), on the West Java coast, Indonesia, in 2022.

MATERIALS AND METHODS

Study area

The northern West Java coastal areas, Indonesia, consisting of Jakarta and Subang (western part/ West Java coast), were selected as the study areas representing disturbed and intact sites, respectively (Fig. 1). The determinations of disturbed and intact sites were based on literature reviews, field

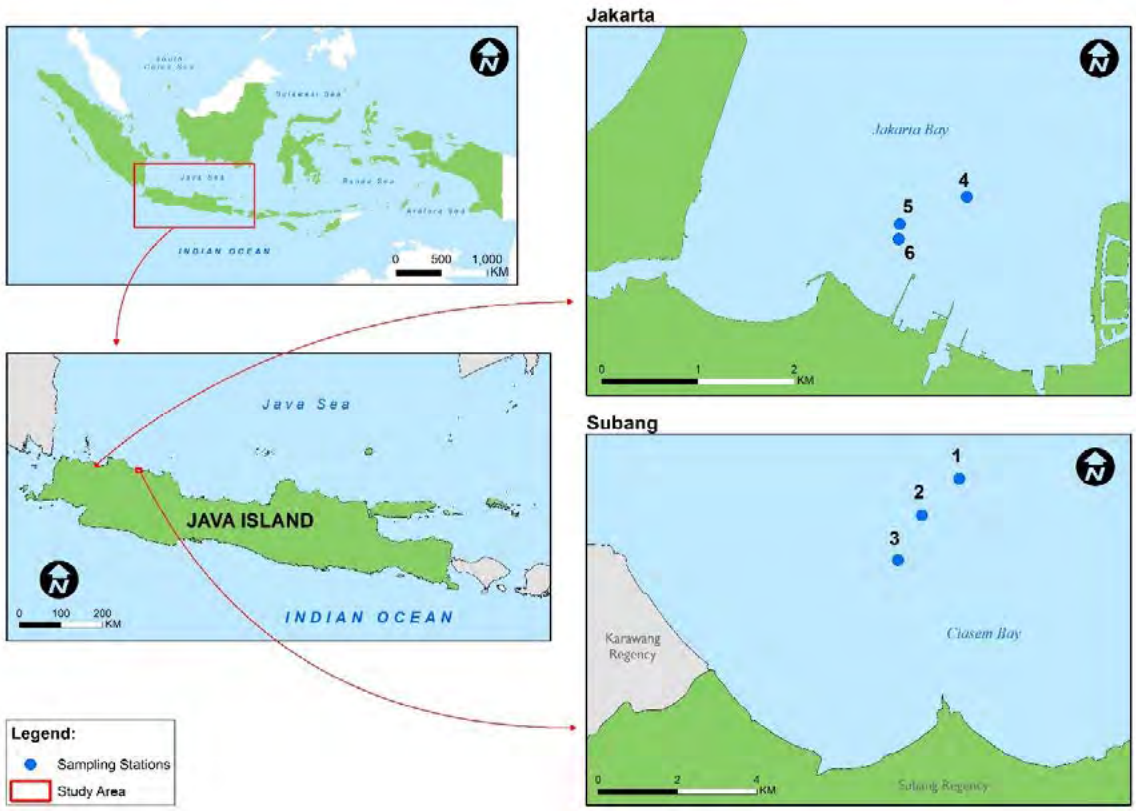

Fig. 1: Geographic location of the study area at disturbed and intact sites on West Java coast, Indonesia

observations, and satellite image classification using geographical information system (GIS) analyses. The disturbed site was part of Jakarta city, with the geographical location of between 6.103° and 6.108° south latitude (SL) and 106.773° and 106.779° east longitude (EL). These sites are characterized by the absence of natural cover, including mangrove forests, as the natural vegetation has been converted into settlements. Driven by economic growth and high population growth in Jakarta, there have been massive developments of residential and infrastructure areas in Jakarta. Besides the settlements, there are seaports and industrial areas. As a result, residential and infrastructure area expansion has disturbed the mangrove forest cover in Jakarta, reducing mangrove areas by up to 393 hectares from 1998 to 2018 (Rizal and Haykal, 2021). Despite these massive anthropogenic disturbances, the body of water off the coast is still utilized by traditional fishermen to catch some fish species. The population of the disturbed site was 1.8 million. The intact site was part of the Subang district, with coordinates of 6°12'50.4"SL, 107°38'38.4"EL - 6°13'19.2" SL, 107°41'38.4"EL. This sites is characterized by a combination of fishponds with reforested mangroves and the presence of intact mangrove forests. This site was previously covered by vast mangroves. However, those intact mangroves were deforested and converted into fishponds. As a result of awareness of the community and fishermen, the logged mangrove forest has been restored through reforestation. The results were mangroves covered with fishponds. The water near the coast is known to have numerous fish species of commercial value, which can be either consumed or sold in the market. The population of the disturbed site was only 64,235 people.

Fish survey

The procedure for the fish survey was modified from previous studies (Agustriani *et al.*, 2020; Araújo *et al.*, 2006). The survey was conducted in the daytime, from 8.00 am to 14.00 pm. Gillnets

with a mesh size of 2 inches were used to capture fish. The fish collected were preserved using 10% formaldehyde. Fish identification was conducted based on their morphological characteristics, using the identification key provided in the guidebook by Kottelat *et al.* (1993).

Environmental variable measurements

Environmental variables, such potential of hydrogen (pH), salinity, and dissolved oxygen (DO), were recorded in situ. Each variable was noted with three replications for each sampling location. The equipment used to measure the variables were the Lutron DO meter 5510 for DO values, Lutron pH meter 5510 for pH, and Atago refractometer for salinity. The site coordinates were plotted using the Garmin eTrex global positioning system (GPS).

Data analyses

Coastal land uses

A GIS was used to classify land use in the coastal area. Images captured using Landsat 8 were reacquired and supervised to obtain the type of land use. The categories for coastal land-use classifications were water and sea, mangrove, mangrove and fishpond, and settlement. Then, the compositions of each land-use type were denoted as percentages.

Fish species diversity

The diversity of fish species was determined using the Shannon–Wiener diversity index. This index was applied to measure the diversity of fish species in both disturbed and intact sites using Eq. 1 (Roy *et al*., 2022).

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where, H' is the Shannon–Wiener index, pi is the proportion of the total abundance of the community represented by the i-th species, ln (pi) is the natural log of pi, S is the number of fish species encountered, and Σ is the sum of species 1 to species S.

Rarefaction curves and Lorenz graphs

Fish diversity was modeled using the rarefaction curve (Nuon *et al*., 2020) and Lorenz graph. The Lorenz graph indicates diversity based on the evenness. Within the Lorenz graph, the diversity was measured based on the curve shapes under the diagonal line representing the evenness. The greater the curve of the evenness line, the more diverse the particular species becomes and the more uneven the abundance of each fish species becomes (Nijssen *et al*., 1998; Rousseau *et al*., 1999; Tallei *et al*., 2018).

Principal component analysis (PCA), analysis of variance (ANOVA), and x^2-test

PCA, an ordination method, was used to visualize the patterns of diversity values (H') and environmental variable data between the disturbed and intact sites (Chen *et al*., 2022). The significance of the effects of disturbances on the H', DO, salinity, and pH was tested using ANOVA (Caliman *et al*., 2013). The x^2-test was used to test the differences of land-use compositions.

Akaike information criterion (AIC) model

Fish community correlations with environmental variables in both disturbed and intact sites were modeled using AIC, following Cavada *et al.* (2016). The AIC model was developed using linear regression (Smoliński and Radtke, 2017; Wedding *et al*., 2019). The parameters measured included in AIC were AIC_c, ΔAIC_c, AIC_c weight, cumulative weight, and log likelihood. To develop the model, environmental variables correlated with the fish biodiversity index (H'), including pH, DO, and salinity, were analyzed. To investigate which is the best model, the following seven linear mixed-effect models were applied and compared as follows:

Model 1: Salinity effect
Model 2: DO effect
Model 3: pH effect
Model 4: Salinity + DO effect
Model 5: Salinity + pH effect
Model 6: DO + pH effect
Model 7: Salinity + DO + pH effect

The best model was selected based on the lowest AIC_c and cumulative weight values.

RESULTS AND DISCUSSION

Coastal land uses

Land-use characteristics are one of the important pieces of information recorded in this study as they play a significant role in influencing the environmental determinants and fish species diversity. Based on the statistical results, a significant difference in land-use compositions was found (x^2 = 23.532, $P < 0.05$)

(Fig. 2). The coastal disturbed site was dominated by settlements. In comparison, settlements were absent at the intact site. At the intact site, intact mangroves and reforested mangroves were more common and dominant (Fig. 3).

The significant differences in land-use types between both sites affected fish species diversity and environmental determinants. The average fish species diversity, denoted as H', reduced by 53.91% from 2.17 (95% confidence interval [CI]: 1.15–3.19) to as low as 1 (95% CI: 0.018–1.98) (Table 1). Some environmental determinants were also affected (Fig. 4). The water at the disturbed site was becoming more acidic than that at the intact site ($F = 220.516$, $P < 0.05$). The disturbed site had lower salinity because of the presence of 13 rivers at this site that discharge freshwater.

These findings on how coastal land uses influence the ecosystem along with fish species diversity agree with those of previous studies (Qiao *et al*., 2022). In the Southeast Asian region, as observed in Sabah (Tóth *et al*., 2019), land-use changes in protected intact areas reduced the species and functional richness of native fish. Any form of logging or land-use change has had a clear and negative impact on fish communities. As a consequence of anthropogenic disturbances, low H' values can also be caused by the presence of invasive fish species that replace native species. Conversions of intact vegetated areas into agricultural areas have caused non-native fish to modify the structure of native fish communities (Wilkinson *et al*., 2018).

Fish community assemblage

In total, 11 species from 11 families were found in the disturbed site (Table 2). Species belonging to Leiognathidae, Haemulidae, and Sciaenidae were

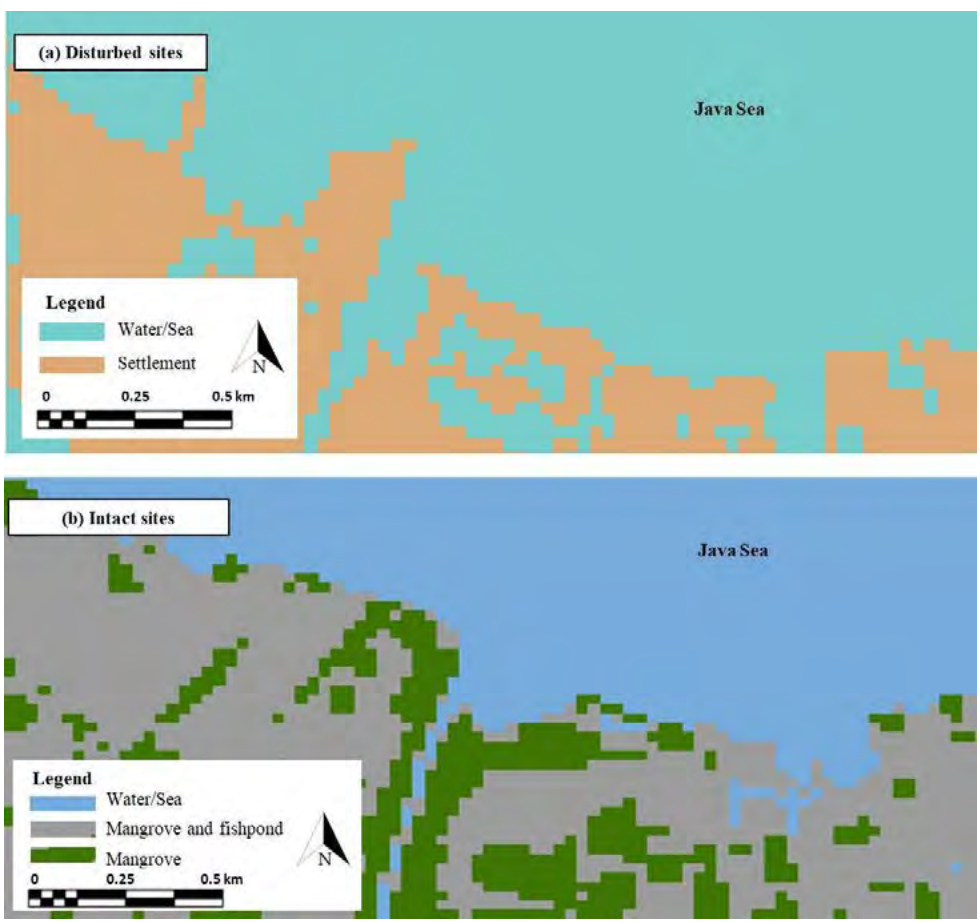

Fig. 2: Land-use classifications at disturbed and intact sites on West Java coast

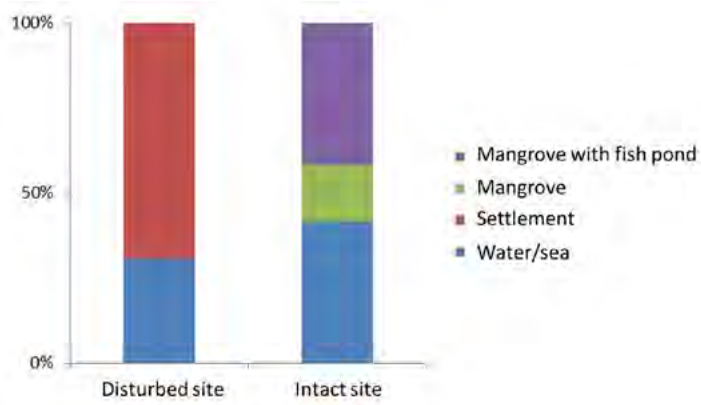

Fig. 3: Land-use compositions at disturbed and intact sites on West Java coast

Table 1: Summary of the mean and 95% CI and ANOVA for effects of disturbances on H', DO, salinity, and pH at disturbed and intact sites

Source of variations	Mean and 95% CI		F	P
	Disturbed	Intact		
H'	1 (0.018–1.98)	2.17 (1.15–3.19)	2.606	0.181
DO	19 (17.3–20.7)	6.33 (6.19–6.47)	220.516	0.000
pH	6.99 (6.76–7.22)	7.7 (7.59–7.81)	29.337	0.005
Salinity	24 (12.6–35.4)	35.5 (34.4–36.6)	3.851	0.121

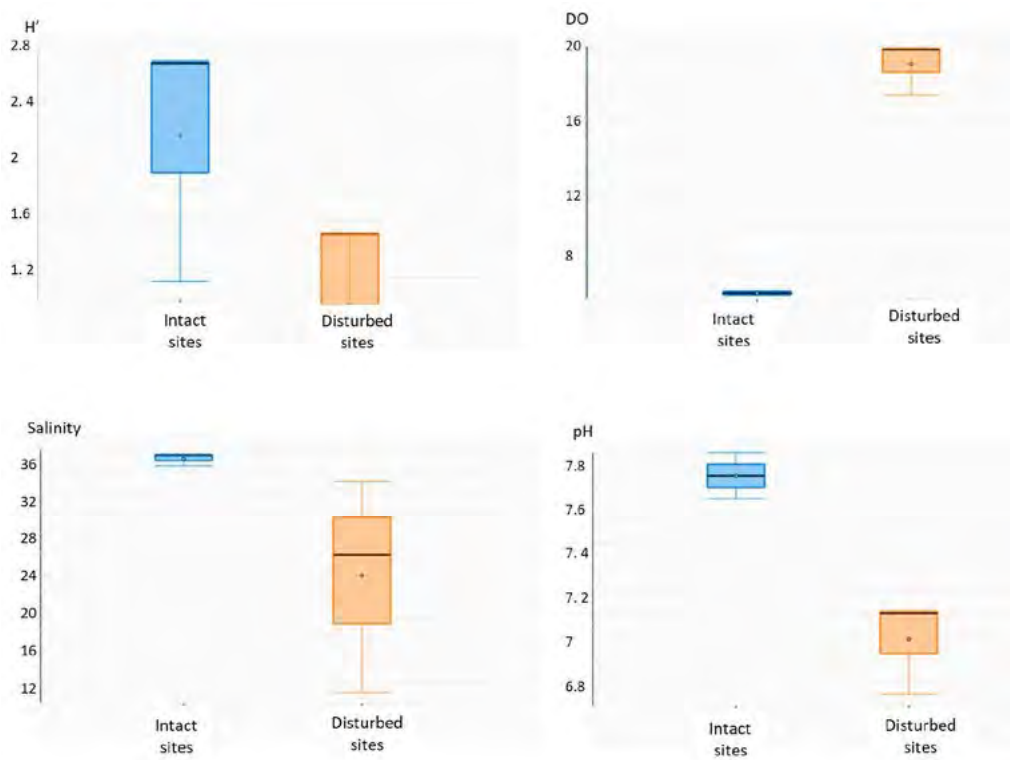

Fig. 4: Comparisons of H', DO, salinity, and pH between disturbed (a) and intact (b) sites on West Java coast

Table 2: Fish species list recorded with family, common name, and individual abundance at disturbed (A) and intact (B) sites on West Java coast

Scientific name	Common name	Family	IUCN	A	B
Leiognathus equulus (Forsskål, 1775)	Common ponyfish	Leiognathidae	LC	6	-
Leiognathus brevirostris (Cuvier and Valenciennes, 1835)	Shortnose ponyfish	Leiognathidae	NE	-	1
Deveximentum insidiator (Bloch, 1787)	Pugnose ponyfish	Leiognathidae	NE	-	3
Photopectoralis bindus (Cuvier and Valenciennes, 1835)	Orangefin ponyfish	Leiognathidae	NE	-	1
Nuchequula nuchalis (Temminck and Schlegel, 1845)	Spotnape ponyfish	Leiognathidae	NE	-	4
Sphoeroides pachygaster (Müller and Troschel, 1845)	Blunthead puffer	Tetraodontidae	V	1	-
Lagocephalus spadiceus (Richardson, 1845)	Half-smooth golden pufferfish	Tetraodontidae	LC	-	3
Sardinella brachysoma (Bleeker, 1852)	Deepbody sardinella	Clupeidae	NE	1	-
Tenualosa toli (Cuvier and Valenciennes, 1847)	Toli shad	Clupeidae	V	-	1
Plotosus lineatus (Thunberg, 1787)	Striped eel catfish	Plotosidae	NE	1	-
Hexanematichthys sagor (Hamilton, 1822)	Sagor catfish	Ariidae	NE	1	12
Scatophagus argus (Linnaeus, 1766)	Spotted scat	Scatophagidae	LC	2	-
Sphyraena obtusata (Cuvier, 1829)	Obtuse barracuda	Sphyraenidae	NE	1	-
Platycephalus indicus (Linnaeus, 1758)	Bartail flathead	Platycephalidae	DD	1	1
Abalistes stellaris (Anonymous, 1798)	Starry triggerfish	Balistidae	NE	1	-
Pomadasys argenteus (Forsskål, 1775)	Silver grunt	Haemulidae	LC	23	-
Larimichthys pamoides (Munro, 1964)	Southern yellow croaker	Sciaenidae	LC	11	-
Pennahia argentata (Houttuyn, 1782)	Silver croaker	Sciaenidae	LC	-	26
Gerres oyena (Forsskål, 1775)	Common silver-biddy	Gerreidae	LC	-	1
Lutjanus russellii (Bleeker, 1849)	Russell's snapper	Lutjanidae	LC	-	2
Lutjanus stellatus (Akazaki, 1983)	Star snapper	Lutjanidae	NE	-	1
Thryssa mystax (Bloch and Schneider, 1801)	Moustached thryssa	Engraulidae	LC	-	9
Upeneus sulphureus (Cuvier, 1829)	Sulfur goatfish	Mullidae	LC	-	2
Epinephelus polyphekadion (Bleeker, 1849)	Camouflage grouper	Serranidae	V	-	1
Scomberomorus commerson (Lacepède, 1800)	Narrow-barred Spanish mackerel	Scombridae	NT	-	1
Lepturacanthus savala (Cuvier, 1829)	Savalai hairtail	Trichiuridae	NE	-	3
Nemipterus virgatus (Houttuyn, 1782)	Golden threadfin bream	Nemipteridae	V	-	1
Pampus argenteus (Euphrasen, 1788)	Silver pomfret	Stromateidae	NE	-	1
Calloplesiops altivelis (Steindachner, 1903)	Comet	Plesiopidae	LC	-	5
Pomadasys kaakan (Cuvier, 1830)	Javelin grunter	Haemulidae	NE	-	6
Cynoglossus lingua (Hamilton, 1822)	Long tongue sole	Cynoglossidae	LC	-	3
Spratelloides gracilis (Temminck and Schlegel, 1846)	Silver-stripe round herring	Spratelloididae	LC	-	2
Sillago sihama (Forsskål, 1775)	Silver sillago	Sillaginidae	LC	-	1
Glossogobius giuris (Hamilton, 1822)	Tank goby	Gobiidae	LC	-	1
Crenimugil seheli (Forsskål, 1775)	Bluespot mullet	Mugilidae	LC	-	23
Eleutheronema tetradactylum (Shaw, 1804)	Fourfinger threadfin	Polynemidae	NE	-	2
Chanos (Forsskål, 1775)	Milkfish	Chanidae	LC	-	1
Terapon jarbua (Forsskål, 1775)	Jarbua terapon	Terapontidae	LC	-	3

DD: data deficient; NE: not evaluated; LC: least concern, V: vulnerable

more abundant than other species and families. At the intact site, there were 29 species belonging to 25 families. Species belonging to Mugilidae, Sciaenidae, and Ariidae were more abundant than other species and families. The presence of high numbers of individuals and families in the intact site confirms that fish species at this site are more diverse and abundant. According to the rarefaction curve and Lorenz graph (Figs. 5 and 6), a small sample taken from the intact site yielded more fish species than a sample taken from the disturbed site. Some fish species were restricted to either the intact or disturbed sites, whereas other fish species were more general. At the disturbed site, 36% of recorded species were found only at this site, and these species include Plotosidae, Scatophagidae, and Sphyraenidae. At the intact site, up to 65% of fish species were found to be limited to this site. About 63% of fish species at the disturbed site were also found at the intact site, and as low as 27% of fish species at the intact site were also found at the disturbed site. As the disturbed site have more common fish species, this indicates that disturbance

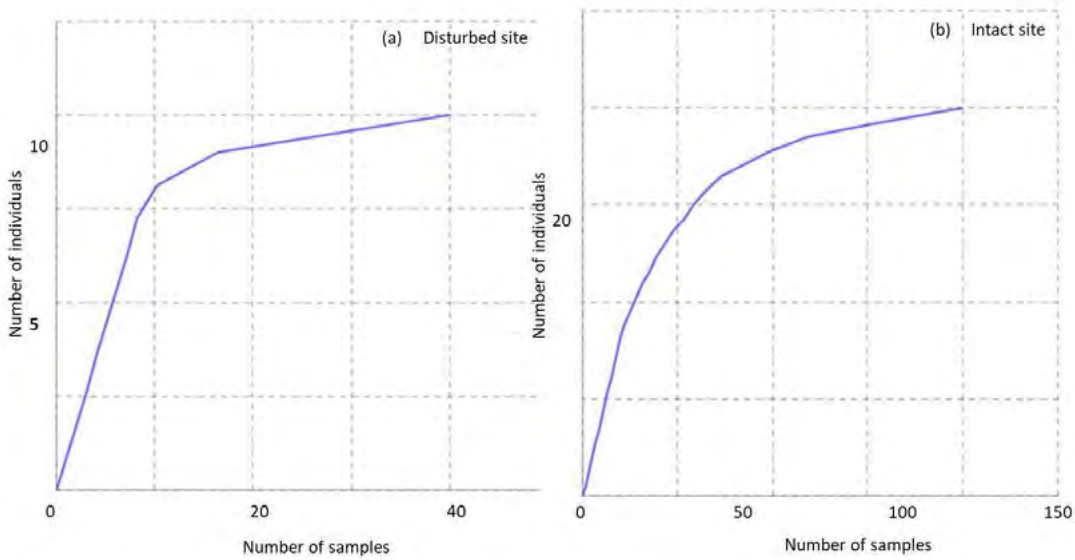

Fig. 5: Rarefaction curves of fish species at disturbed (a) and intact (b) sites on West Java coast

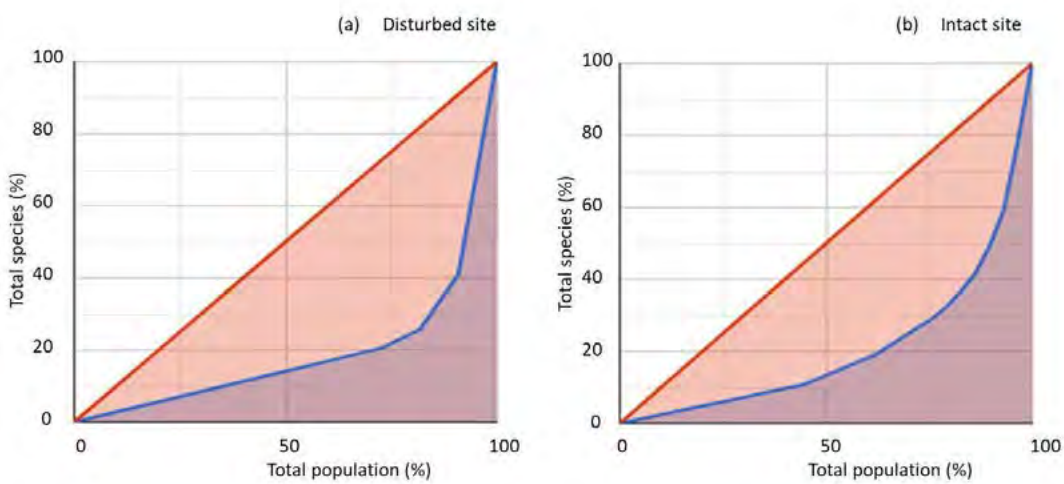

Fig. 6: Lorenz graphs of fish species at disturbed (a) and intact (b) sites on West Java coast

can cause a homogenization of fish species (Fig. 7). Regarding the International Union for Conservation of Nature (IUCN) Red List, more vulnerable and least concern fish species were recorded at the intact site. This indicates that the intact sites make greater contributions to conservation as they provide protection to and habitats for threatened fish species (Fig. 8).

The changing fish assemblages between disturbed and intact sites are related to land use that influences nutrient discharge into the waters. Urban areas with higher human populations are subjected to inputs of anthropogenic waste and characterized by alterations of intact ecosystems to settlements and agriculture, which discharge large quantities of nutrients and waste nitrogen. The accumulation of nitrogen

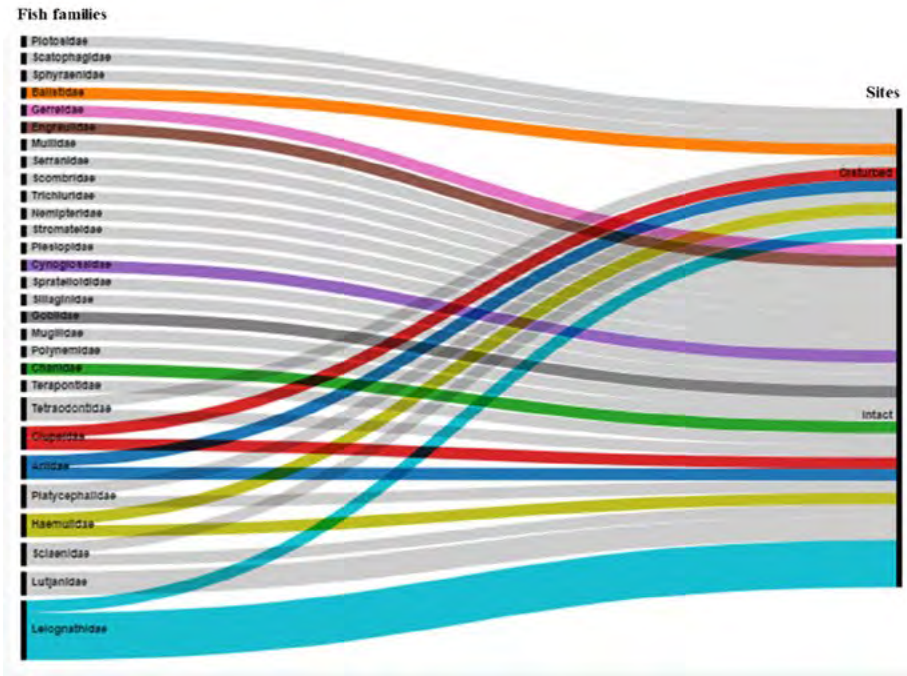

Fig. 7: Fish family compositions at disturbed (a) and intact (b) sites on West Java coast

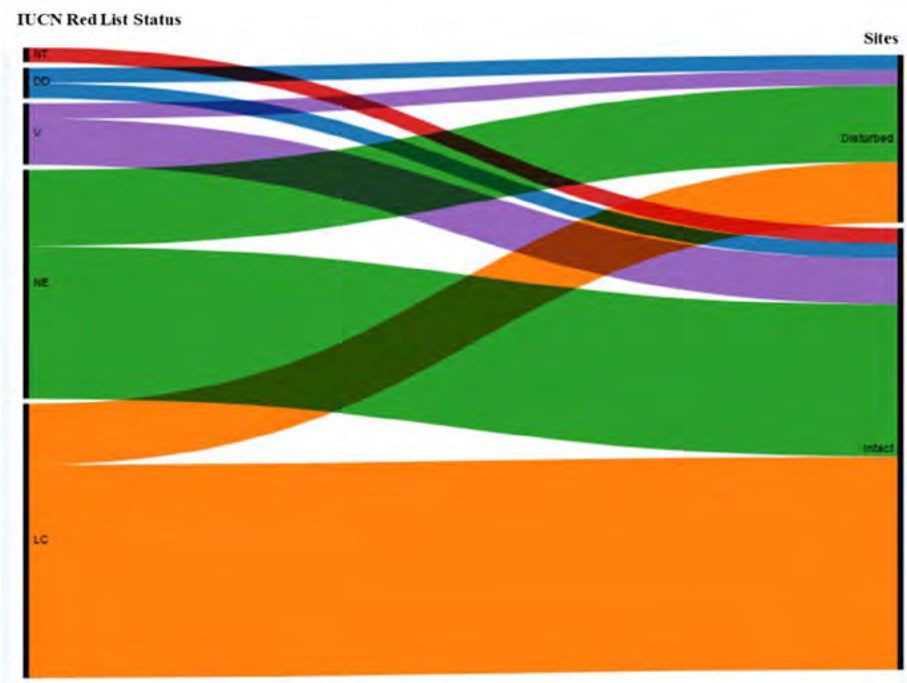

Fig. 8: Fish IUCN Red List Status compositions at disturbed (a) and intact (b) sites on West Java coast (DD: data deficient; NE: not evaluated; LC: least concern, V: vulnerable)

increases the abundant plankton and aquatic plants, followed by increases in planktivore and herbivore species only, which replaces other guilds (Britton *et al*., 2019). Coastal land use for human activities is intrinsically linked to ecological conditions in coastal environments. Nearby mangrove cover removal either at a catchment scale or at a local scale increases the input of sediments and nutrients into coastal ecosystems near terrestrial ecosystems and mangrove cover (Tibúrcio *et al*., 2016). On the contrary, intact vegetation cover is known to improve water quality, availability and stability of physical complex structures, and availability and diversity of food items for fish (Lo *et al*., 2020). As a result, as observed in this study, forested sites host higher fish abundance because fish often actively select mangrove forests in searching for suitable habitat conditions (Castello *et al*., 2022). The presence of mangrove cover benefits the fish community (Hutchison *et al*., 2014) by providing nursery grounds, food resources, and protection from predators. Rogers and Mumby (2019) reported that the presence of mangroves can increase fish productivity.

Fish community and environmental models

The ordination of disturbed and intact sites by PCA of environmental variables (Fig. 9) demonstrated some probable relationships among them. For instance, the intact site was characterized by high diversity, alkaline water with high pH values, saline water, and low DO values. At the intact site, fish diversity tended to be positively correlated with increases in pH, salinity, and DO. Conspicuously, the DO was negatively correlated with fish diversity, pH values, and salinity. In contrast, the disturbed site was characterized by low diversity, acidic water with low pH values, less saline water, and high DO values.

Table 3 shows the model for the fish community and environmental determinants represented by AIC_c and cumulative weight. Two models had the lowest AIC_c and cumulative weight, indicating that they were the best models. These models include the effects of DO and pH determinants. The summed AIC_c and cumulative weight for these determinants were 27.28

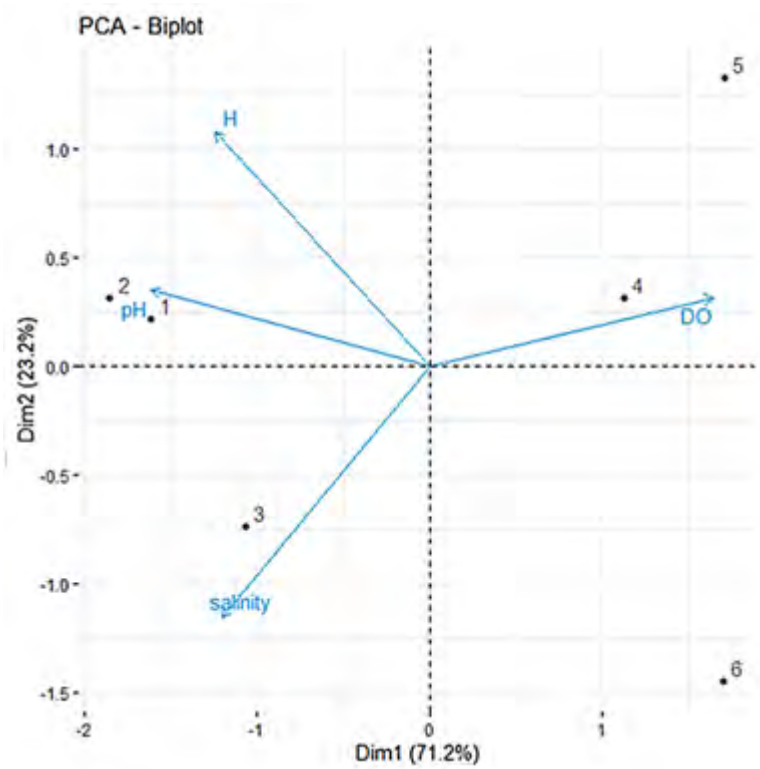

Fig. 9: PCA plot showing intact (1, 2, 3) and disturbed (4, 5, 6) sites related to H', DO, salinity, and pH

Table 3: AIC models of fish diversity (H') with H', DO, salinity, and pH variables at intact and disturbed sites on West Java coast

Fish diversity models	AIC_c	ΔAIC_c	AIC_c weight	Cum. weight	Log likelihood
Model 1: H'~salinity	29.95	2.67	0.14	1.00	-5.97
Model 2*: H'~DO	28.13	0.85	0.34	0.86	-5.07
Model 3*: H'~pH	27.28	0.00	0.5234	0.52	-4.64
Model 4: H'~salinity+DO	57.66	30.38	0.00	1.00	-4.83
Model 5: H'~salinity+pH	57.28	29.99	0.00	0.00	-4.64
Model 6: H'~DO+pH	57.28	30.00	0.00	1.00	-4.64
Model 7: H'~salinity+DO+ pH	na	na	0.00	1.00	-4.63

Table 4: Comparisons with current studies on fish community

Region	Location	Species	Data analysis	Source
Indonesia	Lake Siawan, West Kalimantan province	57	Shannon–Wiener H'	Haryono (2020)
Indonesia	Banten Bay, Banten province	52	Shannon–Wiener H'	Sugiarti *et al.* (2021)
Indonesia	Paraja Bay, Banten province	106	Shannon–Wiener H'	Mujiyanto *et al.* (2021)
Malaysia	Bidong island, South China Sea	89	Shannon–Wiener H'	Rumeaida *et al.* (2014)
Thailand	Ban Pak Klong, Trang province	62	Shannon–Wiener H'	Phinrub *et al.* (2014)
India	Western coast	212	Fish community index	Bella *et al.* (2021)
Indonesia	Jakarta, Jakarta province	29	Shannon–Wiener H', AIC model	This study
Indonesia	Subang, West Java province	11	Shannon–Wiener H', AIC model	This study

and 0.52 for pH determinants and 28.13 and 0.86 for DO determinants, respectively. The summed AIC_c and cumulative weight for Akaike weight as low as 27.28 and 0.52 indicate significant effects of pH variations on fish species diversity. The second important effect was DO, followed by salinity. Then, the suggested model equations are H'~DO and H'~pH. The other five models of fish communities that incorporate salinity and the combined effects of salinity and pH, salinity and DO, salinity and DO and pH, and DO and pH were not suggested because those models have higher AIC_c and cumulative weight values than the suggested best models.

Cum., cumulative; na, not available

AIC was chosen and used as one of the methods for determining which environmental determinant has the greatest impact on specific fish diversity. This method has been used to model the effects of various environmental determinants, including the year, lunar cycle, and tide, on several fish families (Powell *et al.*, 2016). This study is comparable with current research on fish communities at the national, Southeast Asian, and Asian levels (Table 4). Studies in numerous Indonesian provinces represent the current work on the fish community at the national level. Meanwhile, studies in Malaysia and Thailand represent the current Southeast Asian work. A study from India represents the current work on the fish community at the Asian level. However, the current studies have a limitation in their methods. The data analysis method in most current studies is limited to the Shannon–Wiener H'. To fill this gap and provide a better understanding of the fish community along with its determinant factors, this study implemented the AIC model as the sole data analysis method. This is clearly progress compared to current similar studies in that there is a paucity of fish community modeling. In this study, AIC was used to determine that pH is the environmental determinant that most affects fish species diversity. At the intact site, the environmental condition is indicated by the alkaline water with a higher pH that has converse effects on fish species diversity. In comparison, water at the disturbed site is more acidic and it reduces fish species diversity. These findings are in agreement with those of previous studies. In acidic aquatic environments, the aquatic organism diversity was lower than that in acidic aquatic environments with higher pH, and these results were statistically significant. It is clear that acidification (Spyra, 2017) negatively affects ecosystem function (Alam *et al.*, 2021) and diversity because of the elimination of fish species that are

most sensitive to the low pH of water (Hall-Spencer and Harvey, 2019).

CONCLUSION

The coast is an important area because it is basically composed of various ecosystems, including mangroves, coral reefs, sea grasses, and sandy beaches, which are interrelated with each other. Coastal areas are also influenced by various kinds of anthropogenic activities, either directly or indirectly, as well as natural processes that are found on land and at sea. Here, this study succeeded in modeling coastal fish communities on the northern West Java coast, covering both disturbed and intact sites. This study has added value to current research on the fish community by using an AIC model. The AIC model of the fish community resulting from this study can be applied to other coastal areas affected by anthropogenic activities. The model can be used to determine which environmental factors should be regulated to restore and conserve the fish community. This study confirms that the numbers of fish species found at the disturbed site were lower than those at the intact site. More fish species are found at the intact site with H' values of 2.17, and vulnerable species are found at the intact site compared to the disturbed site. The fish community showed lower homogeneity at the intact site, which indicated that more species could thrive at the intact site and more niches were available within the ecosystem. In this AIC model, three main environmental determinants of DO, pH, and salinity were tested for their relative impacts on fish biodiversity. The model discovered that the most important factor in determining fish biodiversity was pH. Based on the model, the summed AIC_c and cumulative weight for Akaike weight were as low as 27.28 and 0.52, indicating significant effects of pH variations on fish species diversity. Thus, coastal conservation management should make the maintenance of more natural coastal systems at intact sites their main priority, as well as restore and improve environmental quality at disturbed sites. Both these objectives could be achieved through a moratorium on development and simultaneous mangrove planting.

AUTHOR CONTRIBUTIONS

N.D. Takarina as corresponding author contributed to the funding, proposal, and drafting of the manuscript. O.M. Chuan prepared the manuscript, reviewed the proposals, and verified the data. M.I. Afifudin conducted fish sampling in Jakarta and tabulated the data. L. Tristan conducted fish sampling in Subang and counted and identified the samples. I. Arif prepared the samples and tabulated the data. A. Adiwibowo drafted the manuscript and analyzed and interpreted the data.

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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 have been completely observed by the authors.

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ABBREVIATIONS

^{o}	Degree
%	Percentage
Σ	Sum of species 1 to species S
am	Ante meridiem
ANOVA	Analysis of variance
AIC	Akaike information criterion
AIC_c	Akaike information criterion factor i
ΔAIC_c	Akaike information criterion delta/sum
CI	Confidence interval
DD	Data deficient
DO	Dissolved oxygen
EL	East longitude
F	Means between population/ distribution
GIS	Geographical Information System
GPS	Global Positioning System
H'	Shannon–Wiener index
in	Inch
IUCN	International Union for Conservation of Nature
LC	Least concern
ln	Natural log
N	North
na	Not available
NE	Not evaluated
P	Probability / significant value
PCA	Principal component analysis
pH	Potential of hydrogen
p_i	Proportion of the entire community made up of species i
pm	Post meridiem
S	Number of fish species encountered
SL	South latidude
V	Vulnerable
x^2	Chi square

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CASE STUDY

Proximate values and elemental analysis in wheat and soybean using inductively coupled plasma mass spectrometry

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ABSTRACT

BACKGROUND AND OBJECTIVES: Determining food composition and bioactivity is critical to both theoretical and applied research in food science and technology. This is frequently used to determine the nutritional value and overall acceptance of the food by consumers. The current study's goal is to determine the macronutrient, mineral and antioxidant activity of selected wheat and soybean varieties with the potential to be useful in the food industry to develop value-added products that are safe for consumption.

METHODS: The proximate and mineral composition, gluten characterization, total phenolic contents, and antioxidant activity of three wheat cultivars and five soybean cultivars that are indigenous to India were studied.

FINDINGS: Wheat varieties were found to be rich in carbohydrates (65.8-68.8 percent) and gluten (27.2-28.6 percent), whereas soybean varieties were found to be the richest source of protein (32.8-33.7 percent), fat (17.1-17.6 percent), fiber (21.7-28.8 percent), polyphenols (2.76-3.59 milligram gallic acid equivalent per gram, and antioxidant activity (97-123 microgram ascorbic acid equivalent per gram). These samples were also found to have significant content of essential minerals.

CONCLUSION: The tested samples had a high nutritional value and energy content and could be a good source of nutrition for a large population. A comprehensive report on the proximate and mineral composition, total phenolic content and antioxidant activity of the wheat and soybean varieties collected from the Rewa district, India, was reported.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
68	2	5

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INTRODUCTION

Wheat (*Triticum aestivum)* is among the most significant cereal crops grown worldwide and a staple for nearly 2.5 billion people (Reynolds and Braun, 2022). Wheat is a major source of protein in low- and middle-income countries, as well as a good source of calories and dietary fiber. Wheat consumption lowers the risk of chronic diseases such as obesity, diabetes, cardiovascular disease, and cancer due to bioactive components (Liu *et al*., 2020). Flavonoids, phenolic acids, alk(en) resorcinol's (Ars), benzoxazinoids (Bxs), phytoestrogens, tocopherols and tocotrienols, carotenoids, and other minor components, along with dietary fiber in wheat, have been found to benefit human health (Tian *et al*., 2022). Soybeans (*Glycine max*) have emerged as the "golden bean of the twenty-first century" due to the potential health benefits obtained from consumption (Nwosu *et al.*, 2019). It is an East Asian legume with high protein levels comparable to animal proteins because it is the only vegetable source that contains all essential amino acids (Singh *et al*., 2019). Soybean bioactive components such as isoflavones, peptides, saponins, and phytosterols have been shown to be beneficial to health (Swallah *et al*., 2022). The availability of phytoconstituents and nutritional quality of wheat (Tian *et al*., 2022) and soybeans (Alamu *et al*., 2019) influenced by a variety of factors including genotype, pedoclimatic, processing, and consumption pattern. India is one of the leading producers of wheat and soybeans (MAFW, 2022). Wheat accounts for a significant portion of the food basket in a vastly populated country like India, accounting for 36% of total food grains produced, ensuring not only food security but also nutritional security (Sendhil *et al.*, 2019). Soybean production and consumption in India is expected to increase due to its nutritional value and favorable agro-climatic conditions (Kolar *et al.*, 2021). Given the various health benefits attributed to the bioactive components in wheat and soybeans, there is a growing interest in exploiting wheat and soybeans to develop functional foods, which is facilitated by a thorough understanding of the nutrient profile (macro and micronutrients) variability among different genotypes of wheat and soybean cultivars, which could aid in the identification of raw materials for improved product development. Significant and increasing consumption of wheat and soybean, as well as widespread public distribution in India, is also associated with major concerns such as increased exposure to toxic heavy metals that affects human health (Suman *et al.,* 2020). Indian soybean cultivars are found to be sensitive to phytotoxic ozone levels (Mukherjee *et al*., 2021) and crop heat stress (Sun *et al*., 2019), resulting in lower yield and nutritional status. Mineral composition is as important to human health as bioactive constituents in the maintenance of the enzymatic system, vitamin synthesis, and haemoglobin formation (Kashyap *et al.*, 2022). Wheat and soybeans are rich in essential minerals such as zinc, copper, iodine, manganese, sodium, potassium, calcium, magnesium, iron, and phosphorus (Noori *et al.*, 2022). Plants typically absorb different elements from soil and water, with different rates of absorption for each element. Soil is an important component of the biosphere that is exposed to a variety of pollutants, including heavy metals released into the atmosphere by both natural and anthropogenic activities (Kumar *et al*., 2019). The increase in heavy metal content has a biomagnification effect on all organisms. Heavy metals with high transfer coefficients, such as cadmium and lead, are easily absorbed by plants because of technogenic emissions (Chaplygin *et al*., 2018) and mining activities (Wu *et al*., 2021). Madhya Pradesh is one of the leading states in India in terms of wheat and soybean production (DES, 2021), and it also has the second highest number of mines in the country as per the report the Ministry of Mines, Government of India in 2018 (Kumar *et al*., 2019). Heavy metal estimation, as well as elemental composition estimation, is critical in Madhya Pradesh wheat and soybean cultivation, using sensitive and accurate analytical techniques that could help to demonstrate the impact of environmental pollution on the possible bioaccumulation of heavy metals in toxic levels in agricultural produce. Unsustainable agricultural practices, such as excessive nitrogen fertilization, endanger soil fertility and deprive plants of essential elements. To draw possible conclusions on the aspect of functional food development and the influence of genetic variability and environment on the availability of bioactive constituents, it is critical to understand the status of nutrient and elemental composition in wheat and soybeans using well-established protocols (AOAC, 2000). The nutritional quality of a food substance can be determined by evaluating its proximate composition (moisture, ash, protein, fat, fiber, carbohydrates, and total energy)

for macro and micronutrient content. To determine the level of heavy metal contamination, the safety of a specific food substance for consumption and consideration for further development could be evaluated using highly sensitive and accurate analytical methodology. Gluten, a protein fraction rich in the multifunctional gliadin and glutenin found in wheat, is an important determinant of wheat quality, imparting cohesiveness, and elasticity to wheat flour (Zhang *et al*., 2022). The elasticity and extensibility of wheat dough are influenced by the quality and quantity of gluten in wheat, which is an important aspect of the baking industry. Gluten content is directly related to wheat grain protein, which is greatly influenced by the soil microclimate, which combines the effects of temperature, water content, and aeration (Schopf *et al*., 2021). The genetic variation among wheat cultivars has a significant impact on the qualitative characteristics of gluten (Amiri *et al*., 2018). Soybeans are the richest source of polyphenols, and since soybean polyphenols have antioxidant properties (Khosravi and Razavi, 2021), the phenolic content of soybeans, and their ability to exhibit anti-oxidant activity, is a major determinant of their nutritional value (Choi *et al*., 2020). Out-of-limit heavy metal concentrations, such as cadmium, copper, lead, and zinc, are determinants of heavy metal contamination and potential risk to human health (Sobhanardakani *et al*., 2016). The current study's aims are to determine the macronutrient, mineral and antioxidant activity of selected wheat and soybean varieties with the potential to be useful in the food industry to develop value-added products that are safe for consumption. This study was conducted in 2021 at the DRDO-Defence Food Research Laboratory in Mysuru, India.

MATERIALS AND METHODS

Samples

Three wheat cultivars: LOK-803, HI-1544, and LOK-273, and five soybean cultivars: Ahilya 1 (NRC-2), Ahilya 2 (NRC-12), Ahilya 3 (NRC-7), Pratap Soya (RKS-18), and Shakti (MAUS-81) were collected from local farms cultivated using conventional farming methods in the Rewa district, Madhya Pradesh, India. collected samples were stored at -4°C in a temperature and humidity controlled cold room (Bluestar, India) until further analysis. Collected samples were powdered using laboratory flour mill (Softel, India) prior to the analysis.

Chemicals and equipment

Sulfuric acid (98%, H_2SO_4), Sodium hydroxide (NaOH), Boric acid (H_3BO_3), 0.1 N Hydrochloric acid (HCl) solution, 6N HCl, sodium chloride (NaCl) and sodium carbonate buffer are were procured from Merck Life Sciences Pvt. Ltd., Mumbai, India. For the elemental analysis, 60% ultra-pure nitric acid, and 31% ultra-pure hydrogen peroxide solution were purchased from Thermo Fisher Scientific India Pvt. Ltd., Mumbai, India. Proximate analysis of the collected samples was performed using the following equipment: hot air oven (Heratherm, Thermo Scientific, Germany), fiber extractor (Fibrethem, Gerhardt, Germany), muffle furnace (Thermotek electric furnace, Mysore), fat extractor (Soxtherm, Gerhardt, Germany), and fully automated kjeldahl analyzer (Kjeltech™ 8400, Foss, Sweden) equipped with a block digestor, neutralizer, and autosampler. The elemental analysis was performed using a Titan MPS Microwave Sample Preparation System (Perkin Elmer, Inc., Waltham, MA, USA) and a NexION Inductively Coupled Plasma Mass Spectrometer (Perkin Elmer, Inc., Waltham, MA, USA).

Gluten content of different wheat cultivars

The gluten extraction was performed in accordance with the protocol as mentioned in American Association of Cereal Chemists (AACC, 2005). About 25 gram (g) of wheat flour were used to make the dough with the 3% sodium chloride solution. For 40 minutes, the dough was immersed in water. The dough was washed with a stream of running water to remove the starch and other soluble, insoluble, and lipid components until a clear wash water was obtained. The isolated gluten was allowed to stand in water for 1 hour before being dried to the maximum extent possible before being weighed to determine the wet gluten content (weight of wet gluten × 100/ weight of flour). To determine the dry gluten content (weight of dry gluten × 100/weight of dry gluten), the moist gluten was freeze-dried at -46°C for 48 hours. The minimum gluten content of wheat flour should be around 24% (wet) and 8% (dry) (Singh and Singh, 2006). The physicochemical properties of extracted gluten, such as moisture content (wet and dry gluten), water absorbing capacity (dry gluten), and oil absorbing capacity (dry gluten), were determined. The moisture content (MC, % = Final weight/Initial weight x 100) of wet (MCWG, %) and dry (MCDG,

%) gluten samples was determined by drying them in an oven at 120°C for 4 hours (AACC, 2005). The water absorbing capacity (WAC) of dry gluten was determined by dispersing dry gluten (500 mg) in 10 mL of distilled water, thoroughly mixing, and agitating for 1 hour, and centrifuging the sample at 5000 rpm for 30 minutes (Sosulski, 1962). The supernatant was removed, and the sediment was weighed to determine the water absorbing capacity (WAC, % = weight of sediment/weight of sample x 100). The oil absorption capacity (OAC) of dried wheat gluten samples was determined by reconstituting the dried gluten (500 mg) in 10 mL of mineral oil, mixed thoroughly, and agitated for 1 hour (Lin *et al*., 1974). Then samples were centrifuged at 5000 rpm for 30 min. The supernatant was removed and sediment was weighed to determine the oil absorption capacity (OAC, % = weight of sediment/weight of sample x 100).

Total phenolic content and DDPH antioxidant assay

The Folin-Ciocalteu method was used to determine the total phenolic content of wheat and soybeans (Kumar *et al*., 2009). 0.1 mL of aqueous-acetone extract (70%) was increased made up to 0.5 mL with distilled water. 0.25 mL of Folin-Ciocalteu reagent and 1.25 mL of aqueous sodium carbonate solution (20%) were added, and the solution was vortexed for 1 minute before being left to stand in the dark for 40 minutes. The absorbance at 725 nm of the resulting blue coloration was compared to a blank. The total phenolic content was calculated as a gallic acid equivalent (GAE) and expressed as µg GAE/g dry material by interpolating the calibration curve range of gallic acid standard solutions (0.1 to 1.0 mg/mL). The antioxidant activity of soybeans was evaluated using 2,2-diphenyl-1-picryl-hydrazyl-hydrate (DPPH) free radical assay (Rai *et al*., 2011). 0.2 mL of aqueous-methanolic (50%) soybean extract was mixed with 2 mL of DPPH solution (0.16 mM) and vortexed for 3 minutes before agitating for 30 minutes at room temperature in the dark. After 30 minutes of incubation, the absorbance at 517 nm was measured with a spectrophotometer, and the DPPH free radical scavenging activity (% = [1-(absorbance of sample - absorbance of blank)/absorbance of control] x100) was expressed as µg of ascorbic acid equivalent (AAE/g) of soybean.

Methodology to perform proximate analysis

The moisture content, ash content, carbohydrate content, nitrogen content, protein content, fiber, total fat, and total available energy of selected wheat and soybean samples were evaluated to determine the proximate composition. The moisture content (%) in the samples was determined using a hot air oven (Heratherm, Thermo Fisher Scientific, Germany) by drying the samples (10 to 12 hours at 90°C) until they reached a constant weight (AOAC, 2000). Fat content (%) in the samples was determined by extraction using petroleum ether in a software controlled Automatic Soxtherm apparatus (C. Gerhardt GmbH and Co. KG, C., Germany) for 4 hours at 60°C-70°C (Noureddini and Byun, 2010). The crude protein was determined using the Kjeldahl method, as described by Nielsen (Nielsen, 2003). The protein content of the samples was determined using a nitrogen-to-protein conversion factor of 5.83 for wheat samples and 5.71 for soybean samples according to 'Jones factors' for conversion of nitrogen to protein (Longvah *et al*., 2017). The crude ash content was determined using a dry ashing method (Thiex *et al*., 2012). The samples were incinerated at 550° C in a furnace (Thermotek electric furnace, Mysore, India) until carbon residue disappeared. The obtained ash was cooled, weighed, and used to determine the total ash content (%). Crude fiber was determined for the digestible portion of the fat free extract which was hydrolyzed away by serially heating it with dilute acid and dilute alkali (AOAC, 2005). The obtained residue was dried and weighed to determine the fiber content (%). The carbohydrate content (%) of a sample was calculated based on the content of protein, fat, fiber, ash, and moisture (AOAC, 2005). The caloric value was calculated by multiplying the percentages of proteins and carbohydrates by a factor of four (kJ/g) and total lipids by a factor of nine (kJ/g).

Protocol to perform elemental analysis using Inductively coupled plasma – mass spectrometry

The Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) (NEXION, Perkin Elmer, Inc., Waltham, MA, USA) with a microwave sample digestor (TITAN MPS, Perkin Elmer, Inc., Waltham, MA, USA) was used in this study. The instrumental conditions: plasma (Ar) gas flow of 15 Liters per minute (L/min); carrier (Ar) gas flow of 1 L/min;

nebulizer (He) gas flow of 0.98 L/min; spray chamber temperature of 2°C; sampler and skimmer cones with nickel tips; plasma power of 1600 W; sample uptake rate of 300 µL/min were maintained throughout the experimentation. NIST® 1567b wheat flour and NIST® 3234 soybean flour standard reference materials (SRMs) were used in this study to validate the method. Prior to ICP-MS analysis, samples were digested as a preliminary step using the previously described method (Bosnak and Pruszkowski, 2014). 1 g sample was weighed accurately and transferred to a pre-cleaned polytetrafluoroethylene (PTFE) sample vessel. Then, 5 mL of 60% ultra-pure nitric acid and 2 mL of 31% ultra-pure hydrogen peroxide solution was added to the PTFE vessel containing sample within to facilitate the digestion of organic matter. The PTFE vessels are loaded onto a microwave digestor operated at high temperature for the sample digestion. At an operating power range of 0-1400 W, the digestion programme included 30 minutes of heating and 15 minutes of cooling. All samples were completely digested, yielding clear solutions that were diluted to a final volume of 50 mL with ultra-pure deionized water. Gold was added to all solutions at a final concentration of 200 µg/L. Blank samples were prepared by microwave digestion of the acid mixture, as previously described. The PerkinElmer pure single and multielement standards were used to calibrate the ICP-MS method (diluted into 10% HNO_3). The calibration standard ranges were determined based on an element's expected nutritional level. Calibration ranges of 0-300 µg/g were considered for high-level nutritional elements such as potassium (K) or sodium (Na); 0-20 µg/g for low/medium-level essential elements such as manganese (Mn) or iron (Fe); and 0-200 ng/g for heavy metals such as lead (Pb) or mercury (Hg). A multielement standard solution containing indium (In), scandium (Sc), germanium (Ge), lithium-6 (^{6}Li), and terbium (Tb) was also introduced online for internal standardisation across the entire mass range. Acetic acid was added to the internal standard solution to compensate for residual carbon from sample digestion.

RESULTS AND DISCUSSION

Gluten content and characterization of dried gluten

The data concerning protein content (%), wet gluten (%), dry gluten (%), moisture content (%), water absorbing capacity (%) and oil absorbing capacity (%) of wheat samples LOK-803, HI-1544 and LOK-273 are presented in Table 1. Gluten content and characteristics are critical factors in determining wheat flour quality (Kulkarni *et al*., 1987). The wet gluten (WG) and dry gluten (DG) contents of the flour from the analyzed wheat cultivars ranged from 27.25% to 28.44% (WG) and 8.08% to 8.51% (DG) with no statistically significant difference (CV = 2.66% and 3.28%) between the cultivars. The WG and DG contents are in accordance with Kaushik *et al.,* 2015, Kaushik *et al.,* 2013, Kumar *et al.,* 2013 and Singh and Singh 2006. The WG and DG contents of wheat cultivars are correlated with the protein content with higher correlation coefficients (r^2 = 0.998 and 0.992), which is consistent with Cho *et al.,* 2018, Başlar and Ertugay 2011, and Kulkarni *et al.,* 1987. Wheat varieties and sowing time have been found to influence gluten content (Coventry *et al*., 2011). Traditional wheat processing methods such as soaking, frying, and parboiling reduce the gluten content (Balamurugan *et al*., 2018). Increased nitrogen treatment was also found to increase gluten content (Cho *et al.,* 2018). The WG content of a wheat flour determines its protein quality and baking quality, while the DG content determines its water absorption capacity. Gluten vitality, an essential aspect of gluten functionality in the baking industry, has been linked to the water absorption capacity (Frederix *et al*., 2004). Freeze-dried gluten extracted from wheat cultivars had water absorbing capacities (WAC) ranging from 257.1% to 286.7%. The WAC of wheat cultivars is highly correlated with the DG content (r^2 = 0.965). The oil absorption capacity (OAC) of wheat flour is an important factor to consider when frying and cooking noodles. The OAC of freeze-dried gluten extracted from wheat cultivars ranged from 260.2% to 283.1% and was found to be correlated with the DG content (r^2 = 0.905). The similarity of WAC and OAC values (r^2 = 0.985) is in accordance with Kaushik *et al.,* 2015; Kaushik *et al.,* 2013; Singh and Singh 2006. When compared to the minimal levels reported by Singh and Singh 2006, the gluten contents (WG and DG) of the examined wheat cultivars are significant, implying their potential industrial application.

Proximate composition of soybean and wheat cultivars

The data concerning the contents of moisture (%), ash (%), protein (%), total fat (%), total fiber (%),

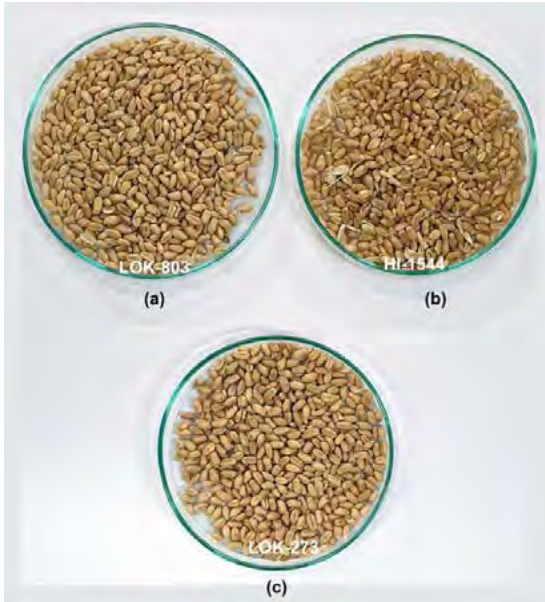

Fig. 1: Wheat varieties collected from the local farms in Rewa district, Madhya Pradesh, India. (a) LOK-803. (b) HI-1544. (c) LOK-273

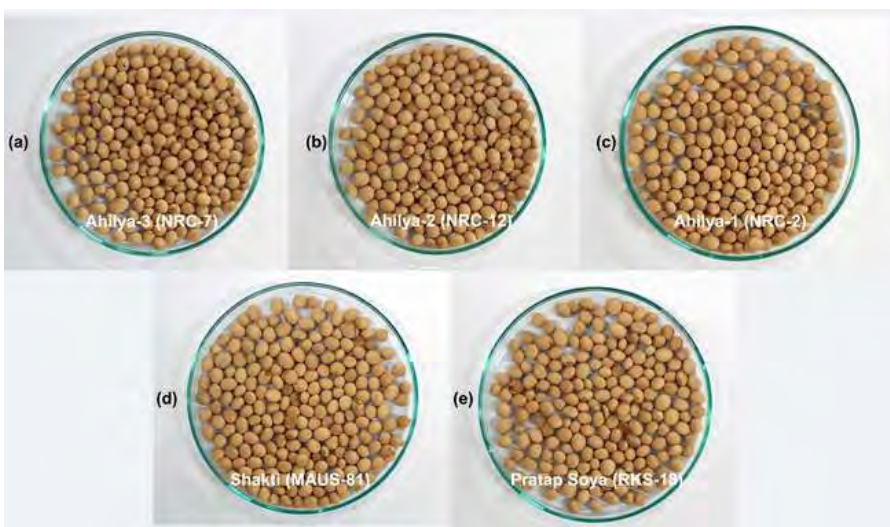

Fig. 2: Soybean varieties collected from the local farms in Rewa district, Madhya Pradesh, India. (a) Ahilya-3 (NRC-7). (b) Ahilya-2 (NRC-12). (c) Ahilya-1 (NRC-2). (d) Shakti (MAUS-81). (e) Pratap soya (RKS-18)

Table 1: Values of protein and gluten composition and gluten characteristics of wheat cultivars

Sample	PC (%)	WG (%)	DG (%)	MCWG (%)	MCDG (%)	WAC (%)	OAC (%)
LOK-803	10.53 ± 0.07	28.44 ± 0.67	8.51 ± 0.15	37.29 ± 0.65	11.56 ± 0.11	279.7 ± 4.89	274.2 ± 3.56
HI-1544	10.58 ± 0.11	28.66 ± 0.63	8.49 ± 0.17	41.75 ± 1.03	12.37 ± 0.15	286.5 ± 3.54	283.1 ± 3.33
LOK-273	10.07 ± 0.14	27.25 ± 0.52	8.08 ± 0.21	32.38 ± 0.73	11.21 ± 0.08	257.1 ± 4.60	260.2 ± 0.82

PC: protein content; WG: wet gluten; DG: dry gluten; MCWG: moisture content of wet gluten; MCDG: moisture content of dry gluten; WAC: water absorbing capacity of dried gluten; OAC: oil absorbing capacity of dried gluten.

Table 2: Proximate values of analysed soybean and wheat cultivars

Sample	Moisture	Ash	Protein	Total Fat	Dietary fibre	Carbohydrate	Energy
	%	%	%	%	%	%	KJ
Soybean samples							
Ahilya 1 (NRC-2)	4.36	1.31	32.85	17.19	22.31	21.94	1564
Ahilya 2 (NRC-12)	5.53	1.29	33.25	17.13	21.72	21.05	1554
Ahilya 3 (NRC-7)	5.02	1.37	33.49	17.16	22.47	20.46	1549
Pratap Soya (RKS-18)	5.66	1.24	33.21	17.57	28.89	13.41	1441
Shakti (MAUS-81)	5.56	1.29	32.88	17.22	27.54	15.49	1458
Wheat samples							
LOK-803	7.85	1.27	10.54	1.341	10.23	68.75	1377
HI-1544	8.40	1.30	10.58	1.508	9.31	68.88	1386
LOK-273	9.07	1.39	10.07	1.682	10.71	67.07	1354

carbohydrate (%) and energy (KJ) for the analyzed soybean samples: Ahilya-1 (NRC-2), Ahilya-2 (NRC-12), Ahilya-3 (NRC-7), Pratap soya (RKS-18), Shakti (MAUS-81) and wheat samples: LOK-803, HI-1544 and LOK-273 are presented in Table 2. The moisture content of soybean and wheat samples ranged from 4.36% to 5.66% ($p<0.05$) and 7.85 to 9.07 ($p<0.05$). The moisture contents of soybean and wheat samples are found to be in close agreement with AL-Amery *et al.,* 2019 and Kassegn, 2018. The lower moisture content of the analyzed soybean and wheat cultivars suggests a longer shelf life (Gebrezgi, 2019). The ash content (an index of inorganic content) of the soybean (1.24% to 1.37%, $p<0.05$) and wheat cultivars (1.27% to 1.39%, $p<0.05$) tested was less than the recommended maximum limit of 1.5%. The ash content of the reported soybean samples was lower than the values reported by Bayero *et al.,* 2019. Soybean cultivars (32.85% to 33.49%, $p<0.05$) contained more protein than wheat cultivars (10.07 to 10.58, $p<0.05$) tested. The protein content of the soybean samples was consistent with that reported by Gaikwad and Bharud 2017, for other Indian soybean cultivars such as KDS-837, KDS-798, JS-335, and DS-9712. Because soybeans have the highest protein content, they are an ideal candidate for processing into a variety of protein-rich foods such as soy milk, tofu, whey protein isolates, and other products that are becoming increasingly popular as a component of the vegan diet around the world (Hess, 2022). Soya bean meal (SBM) is widely regarded as one of the most important sources of protein and essential amino acids in non-ruminant diets around the world (Ibáñez *et al.*, 2020). The total fat content of soybean and wheat samples ranged from 17.14% to 17.57% ($p<0.05$) and 1.34% to 1.68% ($p<0.05$), respectively. The lower content of wheat samples implies that wheat can be stored for an extended period without producing unpleasant odours or oxidizing some fatty acids. Soybeans are found to be rich in carnitine, a bioactive essential fatty acid that has been studied for its role in fat metabolism (Mogensen, 2017). The fiber content of the soybean cultivars tested significantly varied from 21.72% to 28.89%, with Ahilya-2 (NRC-12) having the lowest content and Shakti having the highest (MAUS-81). Wheat cultivars contained less fiber (9.31% to 10.70%, $p<0.05$) than soybeans. Regular soy consumption has also been shown to help lower total cholesterol and low-density lipoprotein cholesterol (Jenkins *et al.*, 2019). Wheat cultivars had a significantly higher carbohydrate content (67.08% to 68.89%, $p<0.05$) than soybeans (13.4 to 21.95, $p<0.05$) in accordance with Ocheme *et al.,* 2018, indicating that wheat is a good source of carbohydrates.

Macro and micro mineral composition of soybean and wheat cultivars

The quantitative data for the microwave digested samples of wheat (LOK-803, HI-1544, and LOK-273) and soybean cultivars (Ahilya 1 (NRC-2), Ahilya 2 (NRC-12), Ahilya 3 (NRC-7), Pratap soya (RKS-18), and Shakti (MAUS-81)) analysed for the content of macro and microminerals: sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), chromium (Cr), manganese (Mn), Iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd) and lead (Pd) were presented in Tables 3 and 4. The calibration ranges specified in the previous section for various levels of elements were reported to show linear responses with excellent coefficient of regression values (r^2 > 0.9998). The macro and micromineral content of wheat cultivars

was compared to certified values of standard reference material (NIST® 1567b Wheat flour). Na, Mg, K (LOK-273), Ca (LOK-803 and LOK-273), Mn, Fe, Cu, and Zn levels were found to be significantly higher ($p<0.05$) than certified levels. Mineral content of soybean cultivars was found to be in significant agreement ($p<0.05$) with NIST® 3234 soybean flour standard reference material certified values. The

Table 3: Elemental analysis of NIST®1567b wheat flour and wheat varieties LOK-803, HI-1544, and LOK-273 using ICP-MS

Element	Sensitivity		NIST® 1567b		LOK-803	HI-1544	LOK-273
	LOD	LOQ	Reference	Observed			
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
^{23}Na	0.010	0.500	6.71 ± 0.21	6.84 ± 0.07	17.5 ± 0.61	25.9 ± 2.4	20.2 ± 1.4
^{24}Mg	0.010	0.500	398 ± 12	408 ± 6.34	498 ± 31	605 ± 9.8	485 ± 13
^{39}K	0.010	0.500	1325 ± 20	1335 ± 11.8	1135 ± 12	1076 ± 10	1712 ± 37
^{44}Ca	0.010	0.500	191 ± 3.3	200 ± 3.09	285 ± 11	175 ± 5.8	327 ± 20
^{52}Cr	0.001	0.008	NA*	0.05 ± 0.01	ND**	ND	ND
^{55}Mn	0.001	0.008	9.00 ± 0.78	8.96 ± 0.37	27.7 ± 0.95	34.9 ± 1.6	39.2 ± 2.9
^{56}Fe	0.050	0.100	14.1 ± 0.33	13.5 ± 0.37	36.4 ± 2.4	42.2 ± 2.6	45.9 ± 4.1
^{60}Ni	0.050	0.100	NA	0.11 ± 0.01	ND	ND	ND
^{63}Cu	0.050	0.100	2.03 ± 0.14	1.93 ± 0.06	4.36 ± 0.41	4.56 ± 0.37	5.16 ± 0.26
^{66}Zn	0.050	0.100	11.6 ± 0.26	11.9 ± 0.53	25.5 ± 1.2	24.2 ± 1.9	25.7 ± 2.3
^{111}Cd	0.001	0.005	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00
^{208}Pb	0.001	0.005	0.01 ± 0.00	0.01 ± 0.00	ND	ND	ND

*NA: Not Available
**ND: Not Detected

Table 4: Elemental analysis of NIST®3234 soybean flour and soybean varieties Ahilya 1 (NRC-2), Ahilya 2 (NRC-12), Ahilya 3 (NRC-7), Pratap soya (RKS-18), and Shakti (MAUS-81) using ICP-MS

Element	Sensitivity		NIST® 3234		NRC-2	NRC-12	NRC-7	RKS-18	MAUS-81
	LOD	LOQ	Reference	Observed					
	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
^{23}Na	0.010	0.500	2.52 ± 0.45	2.32 ± 0.39	2.44 ± 0.23	5.75 ± 0.20	4.06 ± 0.17	4.94 ± 0.25	3.74 ± 0.19
^{24}Mg	0.010	0.500	NA	0.03 ± 0.00	3382 ± 67	2830 ± 65	2633 ± 82	3134 ± 41	2893 ± 50
^{39}K	0.010	0.500	25010 ± 560	24960 ± 436	24436 ± 423	24297 ± 446	21311 ± 441	22642 ± 506	23290 ± 418
^{44}Ca	0.010	0.500	3191 ± 56	3025 ± 59	3097 ± 58	2780 ± 23	3055 ± 48	2975 ± 54	2891 ± 51
^{52}Cr	0.001	0.008	NA	0.05 ± 0.00	4.26 ± 0.21	5.00 ± 0.24	4.40 ± 0.37	4.23 ± 0.20	4.83 ± 1.2
^{55}Mn	0.001	0.008	36.8 ± 0.88	35.3 ± 0.40	36.1 ± 0.56	42.6 ± 2.4	32.1 ± 2.1	58.7 ± 4.1	46.7 ± 2.4
^{56}Fe	0.050	0.100	80.3 ± 2.7	81.0 ± 3.6	85.9 ± 3.3	158 ± 4.5	98.5 ± 3.9	86.5 ± 3.2	101 ± 5.0
^{60}Ni	0.050	0.100	NA	0.05 ± 0.00	9.93 ± 0.49	17.4 ± 0.67	9.97 ± 0.37	10.5 ± 0.40	5.51 ± 0.36
^{63}Cu	0.050	0.100	15.3 ± 0.26	14.8 ± 0.15	14.1 ± 0.96	10.9 ± 0.51	17.3 ± 0.72	28.1 ± 2.9	26.7 ± 2.7
^{66}Zn	0.050	0.100	48.9 ± 1.1		51.3 ± 2.6	55.1 ± 3.1	63.5 ± 3.5	49.8 ± 2.6	80.4 ± 5.1
^{111}Cd	0.001	0.005	NA	ND	ND	ND	ND	ND	ND
^{208}Pb	0.001	0.005	NA		0.02 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.04 ± 0.00	ND

Table 5: Total phenolic content and antioxidant activity of soybean and wheat cultivars

Sample	Total phenolic content (mg GAE/g sample)	Antioxidant activity (µg AAE/g sample)
Soybean samples		
Ahilya 1 (NRC-2)	3.13 ± 0.11	112 ± 2.39
Ahilya 2 (NRC-12)	3.59 ± 0.09	123 ± 1.75
Ahilya 3 (NRC-7)	2.76 ± 0.13	97.1 ± 2.56
Pratap soya (RKS-18)	3.29 ± 0.09	115 ± 2.44
Shakti (MAUS-81)	3.04 ± 0.10	105 ± 2.01
Wheat samples		
LOK-803	1.73 ± 0.02	57.3 ± 1.04
HI-1544	2.21 ± 0.03	62.1 ± 0.86
LOK-273	2.05 ± 0.02	59.6 ± 1.53

results were consistent with those reported by Longvah *et al.,* 2017. According to Pandey *et al.,* 2016 and AL-Amery *et al.,* 2016, the content of macro minerals such as Na, K, Mg, and Ca in wheat and soybean cultivars are higher. Heavy metal levels for wheat and soybean cultivars selected for this study are within recommended dietary allowances for Fe, Mn, Ni, Zn, Cd, and Pb (FSSAI, 2020) suggesting that there is no heavy metal contamination. The findings of this study suggest that consuming soybeans and wheat may help maintain electrolyte balance, which is important for regulating many physiological functions such as acid-base homeostasis, neuronal processes, oxygen transport, bone composition and function, muscular physiology, and so on.

Total phenolic content and antioxidant activity of soybean and wheat cultivars

Polyphenols are important bioactive compounds found in foods that have anti-oxidant properties. The total phenolic content (TPC; mg GAE/g) and the total antioxidant activity (µg AAE/g) of the soybean and wheat cultivars are presented in Table 5. The TPC of soybean and wheat cultivars tested did not differ significantly (p<0.05) from one another, ranging from 1.73 to 2.21 mg GAE/g and 2.76 to 3.59 mg GAE/g, respectively. The results were comparable with Yusnawan, 2018 and *Punia et al.,* 2019, respectively. The total antioxidant activity of soybean and wheat cultivars tested is significantly correlated (r^2 = 0.966) with the total phenolic content. The antioxidant activity of the wheat and soybean samples was in accordance with Yusnawan, 2018 and Punia *et al.,* 2019. The phenolic content and antioxidant activity of soybean cultivars tested were comparable with Mastura *et al.,* 2017; Marathe *et al.,* 2011; Sakthivelu *et al.,* 2008. The phenolic content and antioxidant activity of wheat cultivars tested were comparable with Bhat *et al.,* 2020; Karwasra *et al.,* 2018; Narwal *et al.,* 2014; Revanappa and Salimath 2011.

CONCLUSION

The wheat and soybean samples screened positive for nutritional qualities, particularly protein, fat, and fiber content. Gluten content, an indicator of flour quality, was found in wheat but not in soybean cultivars. Wheat cultivar HI-1544 has the highest gluten content (WG: 28.6%; DG: 8.49%) as well as characteristics such as WAC (286%) and OAC (283%). Besides the high gluten content, wheat cultivars are found to be higher in carbohydrate content than soybean cultivars, with HI-1544 having the highest carbohydrate content (68.8%). Overall, the proximate composition and gluten content of the wheat cultivars did not differ significantly. Soybean cultivars contain more protein (NRC-7: 33.5%), fat (RKS-18: 17.5%), and fiber (RKS-18: 28.8%) than wheat cultivars. The macro and micro mineral compositions of the soybean and wheat cultivars were efficiently analysed with high accuracy and precision, using ICP-MS analysis. The mineral content of most of the analyzed samples was found to be in close agreement with the certified SRM values, with significant levels of macro minerals and heavy metal content falling within acceptable limits. Soybean cultivars had the highest TPC content (NRC-12: 3.59 mg GAE/g), which was found to be directly proportional to the highest antioxidant activity (NRC-12: 123 g AAE/g). The use of SRMs to standardise analyte response in an analytical method also aids in improving the analysis's accuracy and overall performance. Palatability, digestibility, toxicity, and nutritional value of foods,

on the other hand, are important research topics in the development of functional foods. Exploring nutritional aspects aids in the quality improvement of wheat and soybean cultivars for potential use in the development of functional foods. The analyzed soybean (Ahilya 1 (NRC-2), Ahilya 2 (NRC-12), Ahilya 3 (NRC-7), Pratap soya (RKS-18), and Shakti (MAUS-81)) and wheat cultivars (LOK-803, HI-1544 and LOK-273) are found to be rich in macronutrients, macro and micro minerals, bioactive constituents, and free of heavy metal contamination. The nutritional quality of wheat and soybean cultivars could be used to make scientific decisions about the applicability and safety of the nation's food supply.

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AUTHOR CONTRIBUTION

G. Kowmudi performed the experiment execution, data analysis, and manuscript drafting; V. Rashmi assisted technically and performed Inductively coupled plasma mass spectrometric analysis; K. Anoop integrated the data and provided instrumental assistance. N. Krishnaveni, the corresponding author, conceptualised the work, assisted with sample collection, and proofread the manuscript. S. Naveen assisted in evaluating the experimental integrity.

CONFLICT OF INTEREST

The authors 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

AACC	American Association of Cereal Chemists
AAE	Ascorbic Acid Equivalent
AOAC	Association of Analytical Chemists
Ar	Argon
As	Arsenic
°C	Centigrade
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
CV	Coefficient of Variance
DG	Dry Gluten
DPPH	2,2-diphenylpicrylhydrazyl
FAO	Food and Agriculture Organization
Fe	Iron
FSSAI	Food Safety and Standards Authority of India
g	Gram(s)
GAE	Galic Acid Equivalent
Ge	Germanium
H_3BO_3	Boric acid

HCl	Hydrochloric acid
H_2SO_4	Sulfuric acid
Hg	Mercury
ICP-MS	Inductively Couple Plasma Mass Spectrometry
In	Indium
K	Potassium
KJ/g	Kilo Joules per gram
L	Liter(s)
Li	Lithium
LOD	Limit of detection
LOQ	Limit of quantification
MCDG	Moisture Content of Dry Gluten
MCWG	Moisture Content of Wet Gluten
Min	Minute(s)
Mn	Manganese
N	Normality
Na	Sodium
NA	Not available
ND	Not detected
Ng	Nanogram(s)
ng/g	Nanogram per gram
Ni	Nickle
NIST	National Institute of Standards and Technology
NaOH	Sodium hydroxide
OAC	Oil Absorption Capacity
p	Level of significance
PC	Protein Content
Pb	Lead
PTFE	Polytetrafluoroethylene
r^2	Coefficient of regression
Sc	Scandium
SBM	Soybean meal
SRM	Standard Reference Material
Tb	Terbium
TPC	Total Phenolic Content
QC	Quality Control
µL	Microliter(s)
µg/g	Micro grams per gram
µg/L	Micro grams per Liter
µg/mL	Micro grams per milliliter
W	Watts
WAC	Water Absorption Capacity
WG	Wet Gluten
Zn	Zinc

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Podcasts

CASE STUDY

Sub-surface flow constructed wetland for the treatment of sewage generated in a municipal park

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ABSTRACT

BACKGROUND AND OBJECTIVES: The Municipal Park of Areguais is located in the Central Department of Paraguay. Part of this Park is within the area of influence of Ypakarai Lake, which is widely recognized by vacationersfor its natural spaces. Despite being one of the most representative ecological reserves in the country, annual waterquality reports indicate the presence of a high content of pollutants; mainly nitrogen, phosphorus, andfecalcolifoirs, among others. These conditions promote the proliferation of cyanobacteria which consume the available oxygenand compromise the reserve's flora and fauna. Following several laboratory tests, the present work has the objective of evaluating the impact of thepark's recently constructed wetland'son the treatment of residual waters.There are several parameters evaluated in thisstudy of final wastewater discharge disposal treatmentthrough a constructed wetland of horizontal flow with Typhadomingensis. The objective is to develop an adequate system for the treatment of residual waters that can be replicated in places with similar conditions.

METHODS: The evaluation consisted of analyzing the residual water and finding the removal percentage for each of the following parameters such as chemical oxygen demand; biochemical oxygen demand; total phosphorus; total nitrogen; fecal coliforms; hydrogen potential; and temperature. The quality of the treated water was determined by comparing it with the limits established in Article 7 of Resolution Number 222/02 of the Environment Secretary for effluents. The results demonstrate that this system is aviableoption for the removal of fecal coliforms and nutrients such as phosphorus and nitrogen.

FINDINGS: In terms of the quality of the treated water, the parameters studied are within the limits,established by Resolution Number 222/02of the Environment Secretary for Class 2 waters, for water to be discharged into the receiving body. The results obtainedwere: 88.9 percent fecal coliform removal; 84.9 percent total nitrogen; 73.3 percentchemical oxygen demand; 61.4 percent biochemical oxygen demand; and 14.2 percent Total Phosphorus. Considering Resolution 222/02, the biochemical oxygen demand, Total Nitrogen, and Total Phosphorus were outside the admissible limits.

CONCLUSION: It is very feasible for wastewater generated in public parks to be treated through the construction of sub-surface flowwetlands. This study confirms that the treated wastewater is within the establishedlimitsfor all the parameters: temperature, hydrogen potential, biochemical oxygen demand, chemical oxygen demand, total nitrogen, total phosphorus, and fecal coliforms. This model of water treatment can be easily adopted.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
32	9	2

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INTRODUCTION

Biodiversity and the exhuberance of nature are good tourism products. In Paraguay, thevalorization of springs, streams and rivers is achievedthrough rural tourism. The protection of these, along with forests, is therefore prioritized in order fortourists to enjoy this rich natural heritage in a healthy way (López Moreira *et al*., 2018). Ypacaraí Lake is considered to be one of the most beautiful landscapes in Paraguay, surrounded by flora and fauna. It is located between the Central and Cordillera departments, covering an area of 90 square kilometers(km²). It is 24 kilometers (km) long and 6 km wide, with an average depth of 3 meters(m) (SENASA and JICA, 2001).However, many of Paraguay's water resources are critically endangereddue to significant discharges of contaminated water without prior treatment.Residual wateris the liquid that was used by a population or industrythatcontains dissolved or suspended organic and inorganic material (Englande *et al*., 2015), while wastewater refers to water that needs treatment before arriving at its final destination in a receiving body because its initial characteristics have been changed (OEFA, 2014; Rahnman *et al*., 2022). The wastewater discharged into Ypacaraí, as well as other bodies of water, is loaded with different contaminants, including: dyes, solid particles, heavy metals, nutrients, bacteria, and others. This has prompted the prioritisation of applying treatment technologies to clean up the polluted water (Zaboon *et al*., 2022). Over time, different treatment methods have been developed to treat water, each designed according to the characteristics of the wastewater and its desired quality. Many studies have found constructed wetlands with different species of plants to perform well (Zhang *et al*., 2014). Several studies (Saeed *et al*., 2016) have reported on the potential application of groundflow wetlands to improve water quality.When designing these processes, the aim is to accelerate these mechanisms (Piédrola, 2008). Phytoremediation is a set of technologies that reduce the concentration of different compounds from biochemical processes carried out by plants and microorganisms associated with them (Leto *et al*., 2013). An artificial or constructed wetland is a water purification system that uses natural processes for domestic wastewater treatment in shallow water entrusted aquatic species (Swarnakar, 2022). Aquatic plants known as macrophytes can live in permanently flooded land or in water logged conditions for long periods.In recent years, phytoremediation using aquatic plants with high productivities and nutrient removal capabilities has received increasing public attention (Moore *et al*., 2016). *Typha*s sp, commonly known as "Totora", is an emergent aquatic macrophyte that grows in temperate and tropical climate regions and is generally implemented in artificial wetlands to improve water quality in treatment systems (Mufarrege, 2012). It is emergent because it has aerial reproductive organs, and its roots are sunk into the soil at the bottom of the wetland (García, 2010). However, even with all the aforementioned advantages, compared to other existing technologies, it is stillnecessary to evaluate its efficiency according to the specific place and type of effluent to be treated. Within the Paraguayan context, research on wastewater treatment through constructed wetlands present a significant gap in the literature. A few isolated studies have been undertaken on a laboratory scale. Therefore, field studies are required to establish wetland technology as a sustainable approach to wastewater treatment. here has been very limited research on natural and sustainable wastewater treatment methods in Paraguay. Thus, the present study was conducted toevaluate the treatment of wastewater through constructed wetlands in order to find ways to produce treated wastewaterin a way that is less harmful to the environment. Therefore, goal of this study was to evaluate the efficiency of the artificial sub-surface flow wetlandfor the treatment of wastewater generated in the Aregua Municipal Park, Central Department, Paraguay, developed between 2019 and 2020.

MATERIALS AND METHODS

Research location

This study was conducted between September and December 2019, in the Municipal Park of the city of Areguá, located in the Central Department of Paraguay, 20 km away from the Capital city of Asunción (Fig. 1). The project was located within the area covered by the Reserve of Managed Resources of Ypacaraí Lake, coordinates: Latitude 25°18'8.83" S. and Longitude 57°22' 28.19" W. During this study, there was an average rainfall of 120 mm and temperatures (T) ranged between 13.5 to 38 degrees Celsius (°C).

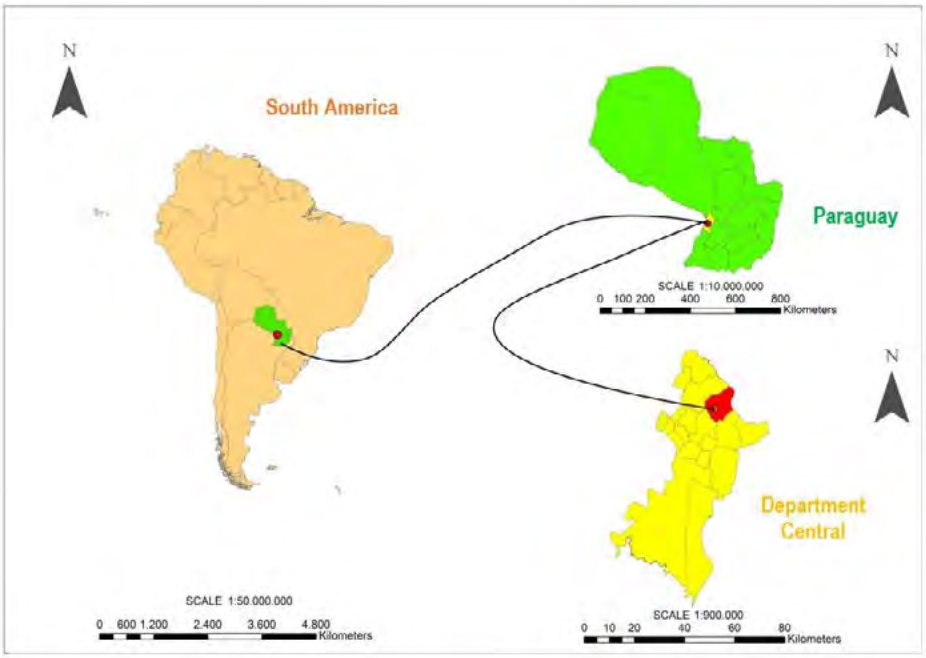


Fig. 1: Geographic location of the study area inYpacaraí Lake, Municipal Park of Aregua, Central Department, Paraguay

Used species

T. domingensis, commonly known as "Totora", is a monocot that belongs to the *typhaceae* family. It is a perennial, herbaceous, rhizomatous, and emergent plant, 1 to 2.5 m tall (Peralta *et al*., 2022). It has leaves with linear blades that equal or exceed the height of the spikes, they are tapered, 40 to 120 cm long by 0.5 to 2 cm wide, with a flat upper side and a slightly convex lower side. Its flowers are unisexual, very small, and arranged in dense spikes. The staminate flowers are in the upper region of the spike, while the pistillate flowers are found in the basal part. The fruit is fusiform, 1 to 1.5 millimeters (mm) long and it blooms in spring. It lives in low-lying areas such as, ditches, lagoons, floodplains,and the edges of estuaries and watercourses. This species is widely studied, both in natural and constructed wetlands, for the treatment of effluentsdue to its high tolerance to contaminants (Mufarrege, 2012; Mukhtar and Abdullahi, 2017; Hazra *et al*., 2015).

Wetland construction

Fig. 2 shows the dimensions of the system designed by Tecno-ambiental S.A. The calculations were made according to a database of effluents generated with a hydraulic retention of 1.62, d = 39 hours (Delgadillo, 2010). A high density polyethylene (HDPE) geomembrane was used to waterproof the system and prevent infiltrations, and it was built with a 2% slope to favor effluent runoff. Ten *T. domingensis* plants were transplanted per square meter (m^2), (300 plants in total) obtained by multiplying seeds from the Multidisciplinary Center for Technological Research's (CEMIT) Biotechnology Laboratory greenhouse. The system was monitored for 90 days to evaluate its development. During this period,the plants reached an average height of 2m while new shoots generated approximately 750 additional plants.

Sampling methodology

To evaluate the efficiency of the wetland, samples were taken at the entry point (M x P1) and the exit point (MxP2), where MX represents the Sample number (5 samples in total). The sampling was carried out consecutively, with 15 day intervals. The samples were transferred to the CEMIT Water Quality Laboratory for analysis.

Parameters analyzed

For in situ determinationsof parameters such as

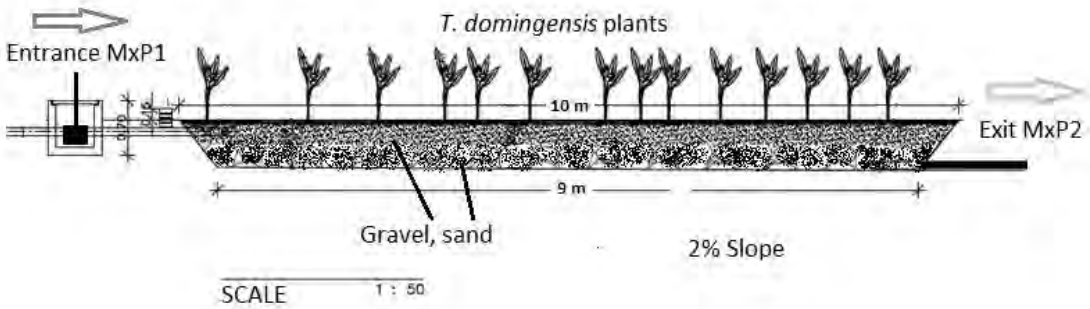


Fig. 2: Cross section of the constructed wetland's design

temperature, conductivity, oxygen, and pH, containers and beakers were used along with multiparametric field equipment.

Methods used for each study parameter

a) Potential of hydrogen (pH): pH measurements were made using a pH meter, as described by Peralta *et al*. (2022).

b) Temperature: T was determined using a portable thermometer. As outlined in Peralta *et al*. (2022), measurements were made directly at the analyzed points.

c) Chemical oxygen demand (COD): COD was established using a closed reflux, colorimetric method. A calibration curve was prepared with five potassium hydrogen phthalate solution standards; 2 mL of the sample was measured and added to tubes filled with 3 mL of digest solution (potassium dichromate, sulfuric acid, mercury fate); it was brought to 150 °C for 2 hours. Then it was allowed to cool and the absorbance was read at a wavelength of 600 nanometers (nm). It was calculated using the formula mg O_2/L = (Absorvance (Abs.) of the sample – Abs. of the blank) × factor × dilution (Peralta *et al*., 2022).

d) Biochemical oxygen demand (BOD): BOD after five days (BOD_5) was found by first bubbling the dilution water (phosphate buffer, magnesium sulfate, calcium chloride, ferric chloride) for 25 minutes. Three dilutions of the samples were made, filling the hermetic flasks with dilution water to the point of overflowing.Then, the dissolved oxygen was measured with the oximeter. The flasks were incubated at 20 °C for 5 days. On the fifth day dissolved oxygen was measured again. It was calculated using the formula: mgO_2/L = (initial dissolved oxygen – final dissolved oxygen) x 300 x dilution (Peralta *et al.,* 2022).

e) Total nitrogen (TN): TN was measured using a macro Kjeldahl method. 250 mL of the sample, 0.5 mL of magnesium sulfate and 10 mL of the digest mix were added into a Kjeldahl flask. This was mixed and digested over a heating device until the mix became clear. Then, it was refilled with 250 mL of distilled water, and homogenized. A 25 mL sample was taken and transferred to an Erlenmeyer flask with alid before adding 25 mL of distilled water, 1 drop of ethylenediaminetetraacetic acid (EDTA) and 1 mL of citrate buffer and homogenizing again. This was later neutralized with 30% sodium hydroxide to a pH of 10. After this, 2 mL of reagent A (dried reagent containing phenol and sodium nitroferricyanide) and 2 mL of reagent B (concentrated reagent of sodium hypochlorite and sodium hydroxide) were added. The mix was homogenized and after 1 hour the calculation was made using the formula: mg/L N = (Abs. of the sample – Abs. of the blank) × factor × dilution (Peralta*et al.,*2022).

f) Total phosphorus (TP): TP was studied using an automated ascorbic acid reduction method. 25 mL of the sample previously digested by the Kjeldahl method (same digestion that was used in the determination of TN). Then, 2 drops of phenol phthalein were added and neutralized with 30% sodium hydroxide until a permanent pink color was obtained. Later a 5 normal (N) sulfuric acid was added by drops, until the mix became clear. Afterwards, 8 mL of mixed reagent (potassium and ammonium double tartrate, ammonium molybdate, ascorbic acid, sulfuric acid) were added and brought to 50 mL. After 10 minutes, the reading was made at a wavelength of 880 nm. The calculation was made using Eq. 1 (Peralta *et al.,* 2022).

Phosphorus (mg/L) = (Abs. of the sample – Abs. of the blank) × factor × dilution (1)

g) Fecal coliforms (FC): MPN procedure was followed for for FC. In the presumptive phase, five tubes with lauryl tryp tose liquid medium were used with 10 mL of sample inoculated in each tube. The samples to be studied were mixed with the medium by gentle agitation. The inoculated tubes were incubated at 35°C. After 24 hours each tube was shaken gently and gas production was observed. Gas formation constitutes a presumed positive reaction. In the confirmatory phase, the primary tubes in which gas was formed were taken. The fermentation tubes containing brilliant green lactose bile were inoculated with a sterile loop (3 mm diameter) and incubated at 35°C for 48 hours. The production of any amount of gas at 48 hours constitutes a positive result. The presumptive tubes that showed some amount of gas during the 48 hours of incubation in the confirmation test were studied (Peralta *et al.,* 2022).

Contaminant removal determination

According to the parameters that were analyzed at the entrance and exit of the system, a calculation of the percentage of removal of the values obtained was made. It was calculated using Eq. 2 (Peralta *et al*., 2022).

$$\%R: \frac{CE - CS}{CE} \times 100 \quad (2)$$

Where;
R: Removal
CE: Entrance concentration
CS: Exit concentration

RESULTS AND DISCUSSION

Physicochemical and microbiological characteristics of the effluent entrance and exit

Table 1 shows the values recorded for each evaluated parameter (hydrogen potential (pH), temperature (T), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), and fecal coliforms (FC)) from the entry (P_1) and exit (P_2) points of the effluent from each different sampling, with the first collected on 09/12/2019 and the last on 11/04/2019.

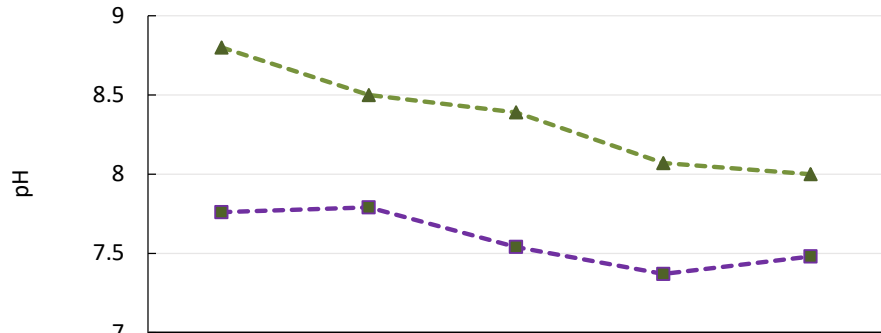
pH

In Fig. 3 the pH values at the entrance (P_1) andexit (P_2)of the wetland are shown. In each instance a decrease in pH (ranging between 8.8 and 7.3) was observedin the samples after passing through the wetland. These results are similar to those found by Peralta *et al*. (2009) who found the pH of the treated wastewater in the wetland to stay close to the pH value of 7,which is considered neutral. The results reported by Samudio *et al*., (2022) controlled test evaluation of another species (*Cyperusgiganteus)* also indicate a pH of around 6 and 5.5 between the control and treated effluent. On the other hand, Delgadillo *et al*. (2010) comment that *T. domingensis*

Table 1: Values obtained in the physicochemical and microbiological analyses

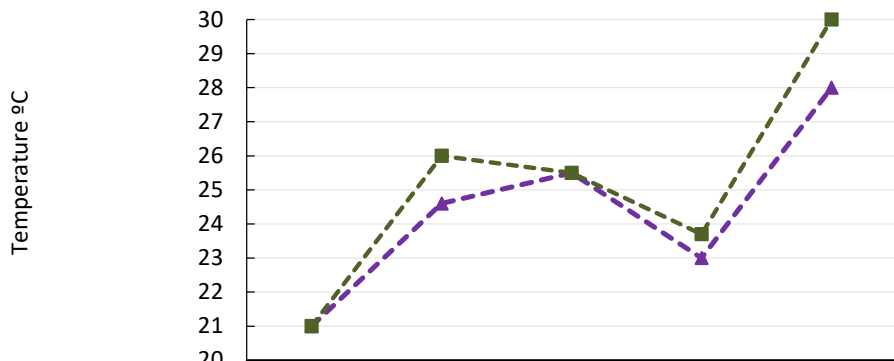
Parameters	Date: 09/12/2019 Hour: 10:26		Date: 09/23/2019 Hour: 10:29		Date: 10/07/2019 Hour: 10:30		Date: 10/21/2019 Hour: 10:40		Date: 11/04/2019 Hour: 10:00	
	1st SAMPLING		2nd SAMPLING		3rd SAMPLING		4th SAMPLING		5th SAMPLING	
	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
pH	8,8	7,76	8,5	7,79	8,39	7,54	8,07	7,37	8,0	7,48
T (°C)	21,0	21,0	24,6	26,0	25,5	25,5	23,0	23,7	28,0	30,0
COD (mgO_2/L)	188,6	97,2	154,71	134,39	49,2	141,25	25,78	52,77	11,43	35,78
BOD_5 (mgO_2/L)	115,5	81,2	81,9	74,1	16,9	26,2	19,9	38,7	9,41	20,25
TP (mg/L)	3,34	1,51	3,27	1,64	4,22	5,69	3,04	1,57	5,41	2,84
TN (mg/L)	56,2	49,3	37,6	25,2	35,1	27,4	21,64	27,98	14,0	5,91
FC (MPN/100mL)	110.000	750	110.000	11.000	110.000	24.000	4.300	230	240	23

Constructed wetland performance for each parameter



	M1	M2	M3	M4	M5
pH Entrance	8.8	8.5	8.39	8.07	8
pH Exit	7.76	7.79	7.54	7.37	7.48

Fig. 3: Temperature of the treated and untreated effluents in the 5 sampling



	M1	M2	M3	M4	M5
Temperature Entrance	21	24.6	25.5	23	28
Temperature Exit	21	26	25.5	23.7	30

Fig. 4: Temperature of the treated and untreated effluents in the 5 samplings

tolerates a wide range of pH (4-9). Therefore, in this system, the development of the plants was not affected by the pH of the wastewater from the toilets.

Temperature

The temperature's tendency to increase is normal, and an increase of 2°C is estimated between the months of September and December. However, between this period (September to December) of 2019, a historical average of 26°C was recorded. This is an increase of 2.9 °C compared to the 1971-2010 average (Grassi,2020).The temperature values did not show large variations between the entrance (P_1) andexit (P_2), as can be seen in Fig. 4.The recorded temperature range remained between 21°C and 30°C. The optimal temperature for the development of bacterial activity is between 25 and 35 °C. During the study the temperatures recorded were close to these values resulting in a good development of bacterial activity. However, according to Espigares (2009) high temperatures present in wastewater have a detrimental effect on thereceiving waters and can potentially modify their flora and fauna, giving rise to the undesirable growth of algae, fungi, etc. Additionally, as the solubility of oxygen decreases with temperature, increasing temperatures can alsocontribute to the depletion of dissolved oxygen.

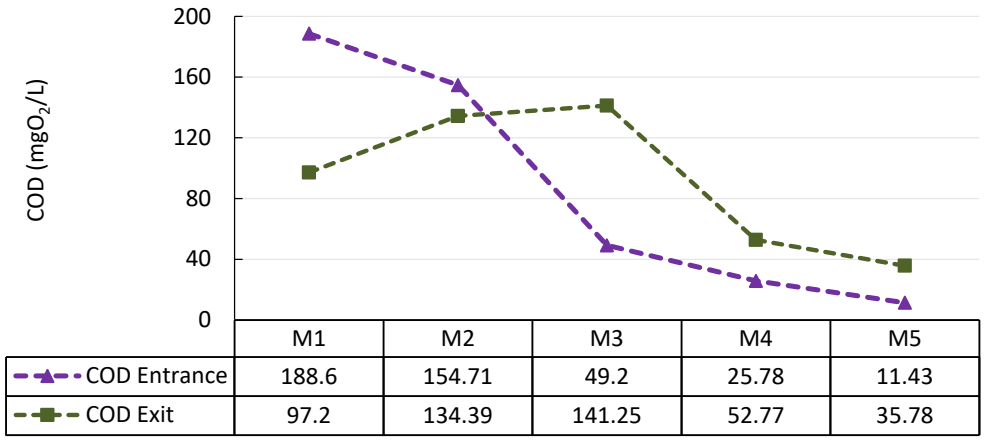


Fig. 5: Biological oxygen demand of the treated and untreated effluents in the 5 sampling

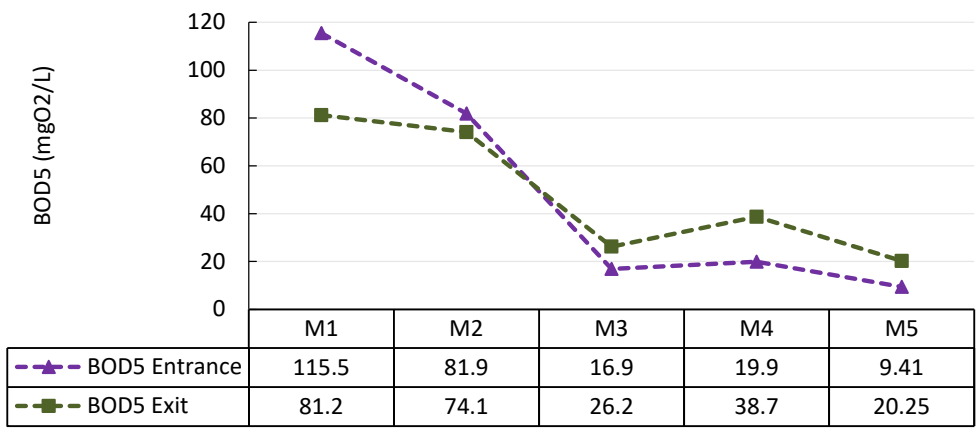


Fig. 6: Biochemical oxygen demand of the treated and untreated effluents in the 5 samplings

COD

The COD values obtained during the study can be observed in Fig. 5, which presents a high degree of variability. The wetland's desired performance was onlyreflected in samplings 1 and 2, where COD decreasedafter the residual water had passed through the wetland. Sampling1 decreased from 188.6 milligram of oxygen per liter (mgO_2/L) to 97.2 mgO_2/L and sampling 2 from 154.71 mgO_2/L to 134.39 mgO_2/L. However, in samplings 3, 4 and 5, higher COD concentrations were recorded at the exit (P_2) of the wetland when compared to the entrance (P_1). As has already been mentioned, this could be due to the residual water from toilets beingunable to fully reach the entrance of the wetland (P_1) due to leaks, resulting in a decreasedamount of water at the exit (P_2). The refore, some sediment was collected along with the sample at the time of collection, which could interfere withthe analysis. In addition, whenconsidering the hightemperatures recorded during this study, the cause of the lower efficiency COD reduction may be the eutrophication that takes placein water exposed tohigh temperatures and consistent solar rays (Samudio *et al*., 2022).

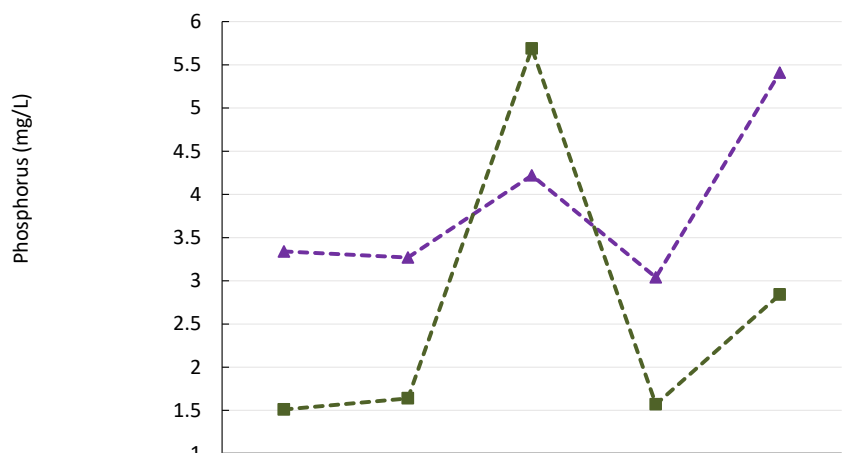
BOD_5

The BOD_5 values evidenced in Fig. 6 followed the same behavior as the COD. This is to be expected as theyare theoretically related processes. According to successive samplings, the wetland's efficiency decreased over time. In sampling 1 the BOD_5 valuedecrease from 115.5 mgO_2/L to 81.2 mgO_2/L,

whilein sampling 2 it decreased from 81.9 mgO_2/L to 74.1 mgO_2/ L. In contrast, in subsequent samplings, higher concentrations of BOD_5 were recorded at the exit (P_2)of the wetland compared to the entrance (P_1). It was considered that the explanation could be the same as for the decrease in COD reduction efficiency. Not withs tanding the above, Osnaya (2012) mentions that in relatively warm climates, although the BOD removal observed during the first days is very fast, subsequent removal can be very limiteddue to the influence of residual BOD production from the decomposition of plant residue.

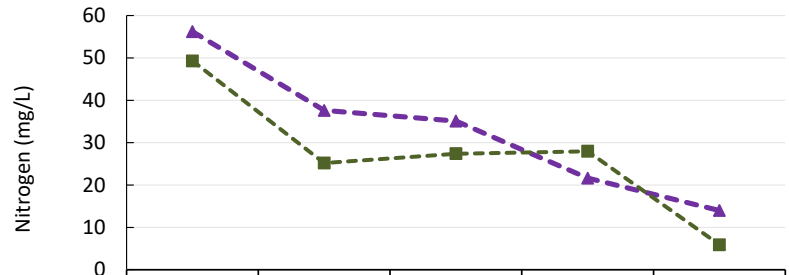
Phosphorus

Phosphate is one of the most salient parameters present in domestic wastewater as detergent is widely used in all domestic activities, especially for washing (Harittash and Bahel, 2015). In this sense, the fluctuations registered may be due to the use of soaps and detergents, which increase and decrease the levels at the effluent entrance (P_1). As can be seen in Fig. 7, in samplings 1, 2, and 4, the recorded phosphorus values behaved in a similar way: phosphorus decreased after the residual water passed through the system. In sampling 5, a value of 5.41 milligram per Liter(mg/L) was recorded at the entrance (P_1) to the wetland with a notable decrease in concentration at the exit (P_2) of 2.84 mg/L. Following the work of Delgadillo *et al*. (2010), these results were expected. The authors reported that the purification potential of wetlands varies seasonally, and that the capacity to treat various factors, including the removal of phosphorus, phosphates and nitrogen, are affected by high summer temperatures and increased plant activity. In the third sampling, a higher concentration of phosphorus was recorded at the exit (P_2) of the wetland (5.69 mg/L) whencompared to the entrance (P_1) (4.22 mg/L). This result could be due to several reasons. Firstly,elementssuch as phosphorus have been reported to be essential for various biochemical and physiological functions in biological systems (Tchounwou *et al.*, 2012). Furthermore, aquatic plants have been reported to accumulate bothmacro and microelement ions through their roots and other organs in concentrations higher than those detected in the water, regardless of whether or not they are necessary for their lives (Tatar *et al*., 2019). Osnaya (2012) offers another explanation, arguing that in wetland systems the removal of phosphorus is not very effective due to the limited contact between the residual water and the soil. Asabsorptionis one of the main mechanisms through which phosphorus is removed, and considering the limited absorption capacities of soil which are subject to saturation, after these sites are occupied no new phosphorus absorption can occur.



	M1	M2	M3	M4	M5
Total phosphorus Entrance	3.34	3.27	4.22	3.04	5.41
Total phosphorus Exit	1.51	1.64	5.69	1.57	2.84

Fig. 7: Phosphorus content of the treated and untreated effluents and the 5 samplings.



	M1	M2	M3	M4	M5
Total Nitrogen Entrance	56.2	37.6	35.1	21.64	14
Total Nitrogen Exit	49.3	25.2	27.4	27.98	5.91

Fig. 8: Nitrogen content of the treated and untreated effluents of the 5 sampling

Total Nitrogen

The behavior of total nitrogen is detailed in Fig. 8. The highest concentration of nitrogen (56.2 mg/L) was recorded at the entrance (P_1) to the wetland in sampling 1.This later decreased to 49.3 mg/L at the exit (P_2). In subsequent samplings, the nitrogen concentration values at P_1 decreased consecutively in each sampling. These reached a value of 14 mg/L in the fifth sampling, which then decreased to 5.91 mg/L at P_2. In sampling 4, a higher concentration of nitrogen was recorded at P_2 (27.98 mg/L) when compared to P_1 (21.64 mg/L). Consideration should be given to the rainfall during the month in which the sampling was carried out. October is one of the rainiest months for the country. Storms are very frequent and some bring strong winds and even hailstorms (DINAC, 2019). These results are similar to those reported by Romero *et al*. (2009), where in some cases the system did not remove nitrogen, but rather nitrification led to the formation of nitrites. This was probably because anaerobic conditions predominated in some areas of the system. In addition the results in rainy seasons show a similar trend: increase of nitrites in water as it passes through the wetlands.Considering the work of Delgadillo *et al*. (2010), the influent nitrogen in the artificial wetland is found as organic or ammonia nitrogen, with low amounts of nitrates. The decomposition and mineralization processes carried out by microorganisms transform this nitrogen into nitrites or nitrates (nitrification), resulting in N_2 (denitrification). The rates of these processes are highly dependent on the oxygen concentration in the system. Gizinska-Górnaet *al*. (2020) evaluated several species, including Salix (*Salix viminalis* L.) and water cabbage (*Phragmites australis*) in several different seasons. They found thatthe efficiency of TN removal was 41%, reaching level shigherth an those established for control organisms. It is crucial to remember that typhas plants can reach 3 m in height, and developvegetativegrowthquickly. Thehigh requirement of elements such as nitrogen, when compared to other species, is there for advantageous.

Fecal coliforms

The values for fecal coliforms obtained during the study can be seen in Fig. 9. In all cases a decrease in fecal coliforms was observed after passing through the wetland system. In samplings 1, 2, and 3, consistent entrance values were obtained: 110,000 most probable numberper 100 milliliters (MPN/100 mL), decreasing to 750, 11,000 and 24,000 MPN/100mL, respectively. This evidences a significant removal of fecal coliforms. In the subsequent samplings (4 and 5), the entrance concentrations of fecal coliforms decreased consecutively. This could be because the residual water generated by toilets did not reach the wetland in its entirety due to leaks, as already mentioned. Regardless, the fecal coliform concentration in residual water decreased after passing through the wetlandin both samplings. Among all the evaluation parameters, the highest removal efficiency was found in the reduction of fecal coliforms. These results support the findings of Peralta *et al*. (2022), who stated that concentrations of

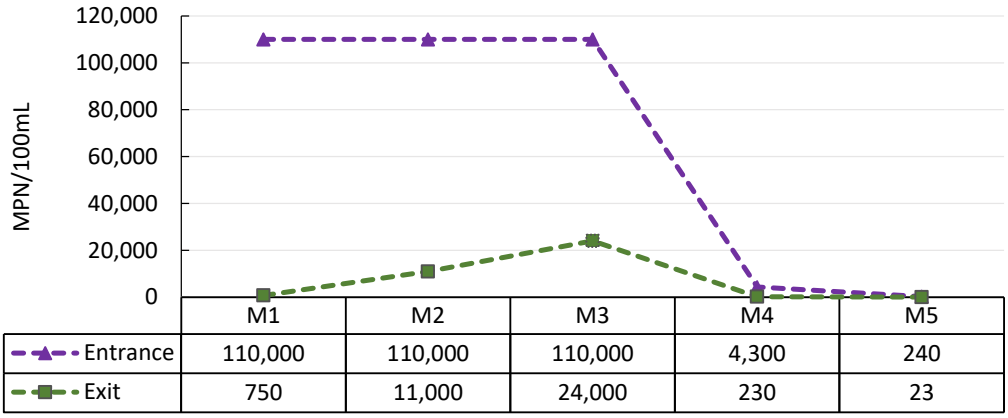


Fig. 9: Content of treated and untreated fecal coliforms in the 5 samplings

fecal coliforms present in wastewater were efficiently reduced in the first sampling. In addition, these results confirm Samudio*et al.'s* (2022) evaluation of *Cyperus giganteus* plants, and the work of Osnaya (2012), who argue that in general, wetlands are able to reduce fecal coliforms by one or two logarithmic orders.

Percentage of removal of studied parameters

This study took place during the period between spring and summer. Osnaya (2012) argues that thepurification potential of wetlands varies seasonally, and that increased plant activity in summer results in a greater removal of fecal indicators and bacteria than in winter. Following this, it was observed that the evaluated parameter with the greatest degree of removal was the fecal coliforms. As shown in Fig. 9, the reduction of these ranged between 78% and 99%. This indicates that the use of the flow wetland system subsurface with *T. domingensis* during the summer season is effective in the elimination of fecal contamination. This efficiency confirms the findings of Delgadillo *et al*. (2010), who suggested that the treatment capacity of wetlands with *T. domingensis* can reach a reduction of 99.9% of coliforms and bacteria. Total phosphorus is the second parameter with the highest removal efficiency in this study. As evidenced by Fig. 7, it was only possible to reach a 50% removal of this nutrient in sampling 1. In the case of sampling 3, a negative valuewas obtained. This is because an increase in phosphorus was recorded at the entrance compared to the exit. The rate of phosphorus removal in samples 1, 2, 4, and 5 ranged between 47.5 and 54%. These values were higher than expectedbecause there are many reports that phosphorus removal is very low in wetland systems. For example, Osnaya (2012) states that phosphorus reduction generally varies between 10% to 20%. In general, the values for the remaining parameters were lower than expected, especially because the design of the wetland system studied was based on nitrogen yield calculations. As shown in Fig. 5, positive COD removal values were only obtainedin samples 1 (48.8%) and 2 (13%). The value for sample 1 is the only one that demonstrates a desired wetland performance, comparable to the work of Arroyave (2010), who found a 45.8% removal of COD in subsurface wetlands with horizontal flow. Samples 3, 4, and 5 all yielded negative removal values: -187%, -103%, and -213%, respectively. The same occured for BOD_5, as shown in Fig. 6. positive values were only given for samples 1 (29.7%) and 2 (9.52%), which are considered extremely low. Subsequent results yielded negative values: for samples 3, 4, and 5, the values were -55%, -94% and -115%, respectively. According to Leto *et al*. (2019), who evaluated identical systems with two different species *Cyperus alternifolius* L. and *Typha latifolia* L., a higher level of BOD_5 removal (72.4%) was obtained for the reed *T. latifolia* L. The authors mentioned that the chosen plant species capacity for vegetative development in the system plays an important role inoverall removal efficiency. Table 2 summarises the efficiency of all the parameters evaluated in this study. The results vary according to different criteria. It is therefore important to consider that the evaluation of the constructed

Table 2: Percentage of removal of physicochemical and microbiological parameters

Sampling	COD	BOD_5	TP	TN	FC
M1	48,4 %	29,7 %	54,7 %	12,3 %	99,3 %
M2	13 %	9,52 %	49,8 %	32,9 %	90 %
M3	-187 %	-55 %	-34 %	22 %	78,2 %
M4	-103 %	-94 %	48,3 %	-29,3 %	94,7%
M5	-213%	-115%	47,5%	57,8%	90,41%

wetland was carried out between September and November. This is a period of time during which climatic conditions such as temperature, solar radiation, rainfall, and others, vary. It has been found that the absorption rate of plants varies according to climatic conditions, therefore, it is argued that the absorption of nutrients and elements also depends on these enviromental conditions. Sayadi *et al*. (2012) reported high removal efficiencies for all contaminants in their study of wetland treatment systems, but highlighted that efficiencies depend on system properties and the operating conditions of treatment systems. In their study, Limoli *et al*. (2016) noted thatsome parameters were subject to pH and wastewater temperature. According to Singh *et al.* (2022) bibliographical work, the literature indicates that the degree of removal of organic compounds (COD and BOD_5) and total phosphorus is not likely to be affected by temperature, but the removal total nitrogen appears to decrease at low temperatures.

CONCLUSION

The treatment of wastewater for subsequent discharge into watercourses in urban and peri-urban environments presents a contemporary challenge. The United Nations' 2021 Report on the development of water resources, "The Value of Water", argues that there is a need for better management of water resources given their current state. In addition, the value of water must be recognized, measured, and expressed, and incorporated into decision making. This is essential for achieving the sustainable and equitable management of water resources, and to achieve the United Nations' Sustainable Development Goals (SDGs) stipulated in the 2030 Agenda for Sustainable Development. It is therefore crucial to look for alternatives for wastewater treatment that are adapted to the needs of each region or country, considering their economy and culture. In this context, constructed wetland systems may be a viable option when deciding on a suitable method. This study found that areduction of the valueswas achieved in most of the parameters studied. In some cases, such asphosphorus, the results were inconsistent. This could be due to climatic variation, such as rainfall, and the concentration of phosphates in wastewater. Article 7 of the SEAM's Resolution Number 222/02 establishes that "Effluents from any polluting source may only be discharged, directly or indirectly, into bodies of water, if they obey the conditions and criteria established in the classification of the receiving body". When evaluating the values of the treated water accordingto the limits established in Article 7, the treated wastewater is considered to be within the limits for all the parametersstudied. The reduction of the following parameters was considered to be highly efficient: TN (57.8%), TP (54.7%) and FC (99.3%). Although the utility of the system should continue to be evaluated, this study offers a significant contribution to the search for more suitable systems for wastewater treatment in public spaces.

AUTHOR CONTRIBUTIONS

A. Vázquez carried out the data collection, experimental design, survey campaigns, effluent analysis, and prepared the text of the manuscript. A. Samudio-Oggero carried out the experimental design, organized the literature review methodology, interpreted the data and results, and edited the manuscript. H. Nakayama organized the methodology, analyzed and interpreted the data and results. I. Cantero organized the methodology and edited the manuscript.

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CONFLICT OF INTEREST

Theauthors declare no potentialconflict of intere-stregardingthepublication of thiswork. In addition, theethicalissuesincludingplagiarism, informedcon-sent, misconduct, data fabrication and, orfalsification, doublepublication and, orsubmission, and redundan-cyhavebeencompletelywitnessedbytheauthors.

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ABBREVIATIONS

%	Percent
°	Degree
′	Minute
″	Second
°C	Degrees Celsius
=	Same
-	Subtract
x	multiply
Abs.	Absorvance
BOD	Biochemical oxygen demand
CE	Entrance concentration
CEMIT	Multidisciplinary Center for Technological Research
cm	Centimeter
COD	Chemical oxygen demand
CS	Exit concentration
d	Days
EDTA	Ethylene diamine tetraacetic acid
Eq	Equation
FC	Fecal coliforms
HDPE	High density polyethylene
h	Hour
Km	kilometers
km^2	Square kilometers
m	Meter
m^2	Square meter
mgO_2/L	Milligram of Oxygen per liter
mg/L	Milligram per Liter
mm	Millimeter
mL	Milliliter
MPN/100mL	Most probable number per 100 milliliters
MxP_1	Sample of point 1
MxP_2	Sample of point 2
N_2	Nitrogen
nm	nanometer
pH	Hydrogenpotential
P_1	Point 1
P_2	Point 2
R	Removal
Res.	Resolution
S	South
S.A.	Anonymous society
SEAM	Environment Secretariat (Paraguay)
T	Temperature
TN	Total nitrogeno
TP	Total Phosphorus
W	West

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CASE STUDY

Sustainability index analysis of microalgae cultivation from biorefinery palm oil mill effluent

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ABSTRACT

BACKGROUND AND OBJECTIVES: Palm oil mill effluent is a liquid waste product of palm oil milling that contains abundant organic pollutants such as nitrogen and phosphorus that are potentially harmful to the environment. However, palm oil mill effluent can be used as a nutrient for the growth of microalgae with utility in pollutant removal and algae biorefinery production of biofuel and functional foods. The aim of the present study was to analyze the sustainability of microalgae biomass production by calculating a sustainability index.
METHODS: Questionnaires were used to evaluate the scientific judgment of expert researchers in the field of microalgae research. Data were processed and analyzed using multidimensional scaling comprising social, economic, ecological, and technological dimensions with a total of 47 attributes in Rapfish software.
FINDINGS: The sustainability index of microalgae biomass production was calculated as 73.53%, which indicates the process has the potential for sustainable development with consideration of the leverage factors identified in each dimension. Analysis of the four dimensions demonstrated that the environment dimension had the lowest leverage at 67.30%, while the economy, technology, and social dimensions had leverage values of 70.99%, 73.67%, and 82.17%, respectively. These findings indicate that management experience and skills (environment and technological dimensions), involvement of family members (social dimension), and productivity level (economic dimension) warrant further attention in order to improve the sustainability of microalgae biomass production.
CONCLUSION: The prospective analysis in the present study identified production, productivity, land conversion, consumption per capita, and population as key or dominant factors influencing the microalgae supply system. Further research is required to fully utilize microalgae biomass as a value-added product in optimal, technically, economically, environmentally, and socially sustainable systems. The results of the present study provide insights into the feasibility of sustainable microalgae biomass production in Indonesia that may inform governmental policies and programs.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
76	5	5

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INTRODUCTION

Production systems using microalgae, including eukaryotic algae and cyanobacteria, represent an alternative method of wastewater treatment that is environmentally friendly and sustainable. This system is also less energy-intensive and currently widely used (Sheehan *et al*., 2017). Microalgae cultivation utilizes the ability of microalgae to absorb carbon dioxide (CO_2) and survive in wastewater using nutrients present in wastewater such as nitrogen and phosphate among others. Untreated palm oil mill effluent (POME) contains large amounts of organic matter in the form of total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), and oil and grease (O and G), which increase the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of POME (Bala *et al*., 2015). POME also contains other macronutrients such as sulfur, potassium, calcium, and magnesium. Micronutrients that are required for microalgae growth and are typically present in POME include manganese, molybdenum, copper, iron, zinc, boron, chloride, and nickel. Certain algal species require other essential elements for growth such as sodium, silicon, cobalt, iodine, vanadine, and selenium (Larsdotter, 2006). A chelating agent (e.g., EDTA) is often added to commercial algal cultures to prevent growth limitation resulting from high concentrations of micronutrients (Oliver and Ganf, 2000). Given their unique characteristics, microalgae are considered to have potential utility in removing pollutants from POME. However, the high organic content of POME may limit the use of POME for the cultivation of microalgae (Low *et al*., 2021). Furthermore, the suspended solids responsible for the dark appearance of POME prevent photosynthesis by microalgae as light is unable to penetrate through POME. Accordingly, pre-treatment of POME is required to optimize the use of microalgae in treating POME (Sari *et al*., 2022). Components of POME including tannins, lignin, and phenolic have been shown to inhibit microalgae growth. Efficient removal of pollutants from POME has previously been demonstrated, including the removal of high proportions of COD, nitrogen (Kamyab *et al*., 2014), and phosphorous (Kietkwanboot *et al*., 2020). These studies demonstrate the potential utility of microalgae in low-cost wastewater treatments, including the treatment of POME. Besides being a renewable source of biomass, microalgae can be used in wastewater treatment as an effective and feasible CO_2 bio-fixation method (Almomani *et al.,* 2019). The primary benefit of using microalgae in wastewater treatment is the formation of oxygen via photosynthesis, which is required for the biodegradation of carbon-containing compounds by heterotrophic bacteria. Previous studies have demonstrated microalgae can promote the elimination of pollutants from wastewater (Chawla *et al*., 2020). The combination of microalgae production and wastewater treatment in industries such as palm oil milling represents an example of a sustainable production system. Previous studies have reported efficient phosphorus elimination using microalgae and the recovery and utilization of phosphorous-rich microalgae biomass from wastewater (Cai *et al*., 2013). Furthermore, microalgae can efficiently capture CO_2 and remove micronutrients from wastewater that may have subsequent utility as potential energy sources (Kamyab *et al*., 2019b). Microalgae can utilize both organic nitrogen (similar to urea) and inorganic nitrogen (as ammonium or ammonia) in addition to nitrites and nitrates (Lage *et al*., 2021). Several microalgae have been cultivated in POME to produce biodiesel such as *Chlorella sp., Dunaliella salina, Chaetoceros calcitrans, Chaetoceros pyrenoidosa, Thalassiosira pseudonana Isocrysis* sp, and *Nannochloropsis oculate* (Kamyab *et al*., 2019a). Analyzing the nutrient content of wastewater provides an opportunity for the recycling of waste products as part of a circular economy. POME has been shown to contain proteins, oil and grease, phenol, nitrogen, phosphate, kalium, iron, sulfate, and ammonia (Mellyanawaty *et al*., 2018). The use of microalgae represents an economic approach to biofuel production as the abundant nutrients present in POME waste can be used as an alternative to expensive chemicals that are otherwise required for the growth of microalgae. The use of microalgae may also reduce energy consumption by utilizing sun light and minimizing the amount of electricity required for stirring (Nur *et al*., 2022). The use of POME has been shown to increase growth of *Chlorella sorokiniana* using a novel photobioreactor design (Cheah *et al*., 2020) and the production of third-generation biofuels (Pal *et al*., 2019). These experiments used microalgae that predominantly contained *Chlorella* sp. in addition to other bacteria, which is representative of natural microalgae found in Indonesia. Microalgae cultivation

using both photobioreactors and open ponds is environmentally friendly as microalgae biomass can be used in biorefinery production, including biofuels (Show *et al.,* 2017), pharmaceuticals, nutraceuticals, cosmetics, and food and feed supplements (Begum *et al.*, 2016). These findings indicate that the nutrients contained in POME may have potential utility in reducing carbon emissions and the environmental impacts of wastewater. Furthermore, the use of POME may enhance the biomass yield of *Chlorella* sp. and therefore increase the yield of biodiesel production. Microalgae biomass resulting from phycoremediation during waste treatment can be used in sustainable biorefinery as a food source or a raw energy material, thereby contributing to a circular economy. Biorefinery from microalgae systems has several advantages, particularly compared to biofuel produced from conventional oilseeds. These advantages include the potential to grow microalgae on non-arable land, increased productivity, and the potential use of wastewater and gas flue as sources of nutrients and carbon to accelerate the growth of microalgae (Nurhayati and Basuni, 2013). State-of-the-art methods of producing microalgae biofuel using POME have demonstrated that microalgae typically out-perform other biomass-producing plants in terms of photosynthetic efficiency. Further, microalgae are capable of producing a wide range of renewable bioenergy sources such as biodiesel, bioethanol, biobutanol, bioelectricity, biohydrogen, and biomethane, among others. According to current research, microalgae appear to be the most promising renewable bioenergy source in Indonesia for replacing fossil fuels. Previous studies have shown that microalgae cultivation using POME reduces production costs. Compared to other biodiesel sources, microalgae represent the most promising substitute for fossil fuels (Table 1)

Indonesia is the largest palm oil producer in the world with a 23.2 million ha plantation area producing 46.22 million tons of crude palm oil (CPO) in 2021 (DGEC, 2021). However, palm oil production has led to the accumulation of huge amounts of POME disposed of as liquid waste. Furthermore, an estimated 5–7.5 tons of water are required to produce 1 ton of CPO (Susanto *et al.*, 2017). Environmental issues associated with POME disposal have led palm oil producers to re-evaluate and develop waste management strategies using a range of techniques. During the past two decades, several biological, physical, and chemical techniques have been reported as methods of treating POME; however, few have been accepted by the palm oil milling industry (Rana, *et al.*, 2017). Calculation of the sustainability index using MDS allows evaluation of the sustainability of biomass and biodiesel production. The impacts of industrialization on the environment have prompted policymakers to consider solutions that increase sustainability (Khan *et al.*, 2018). As the importance of sustainability is increasingly recognized, there is increasing need for instruments that allow the evaluation of sustainability. The sustainability index assesses the status of sustainable developments from the economic (business and industries) perspective while simultaneously evaluating social and environmental impacts. The sustainability index can be used to increase the efficiency and effectiveness of management policies. Technology and the environment are two dimensions that directly and simultaneously affect algae growth. The right environmental conditions can support rapid growth of microalgae (Sofiyah *et*

Tabel 1: Annual production and land required according to biodiesel source (Koyande *et al.,* 2019)

Type of source	Yield of biodiesel (L/ha/year)	Required Land (m^2/kg/biodiesel/y)
Microalgae	58,700–136,900	0.1–0.2
Palm oil	5,366	2
Castor	1,307	9
Sunflower	1,070	11
Repeseed	974	12
Camelina	915	12
Jatropha	741	15
Soybean	636	18
Hemp	363	31
Corn	172	66

al., 2021). Cultivation technologies can also increase algal growth (Harun *et al*., 2010). Accordingly, the creation of suitable environments using cultivation technologies can improve the yield of microalgae cultures. The economic dimension indirectly affects the growth of algae. Given the increasing demand for biomass and biodiesel, an increase in business scale and productivity is expected. Business scaling will likely increase the production POME, thereby potentially increasing algal yield. The social dimension is similar to the economic dimension and does not directly affect algal growth but remains quite important. As an example, levels of education and knowledge regarding environmental conservation (algae utilization) are increasing. However, palm oil producers must choose between the large number of treatment methods available when determining the most suitable waste utilization method according to the company's capabilities and considering the environmental, economic, social and technological impacts of the method chosen. In the present study, practical methods (namely MDS) were used to provide information that may inform CPO industry entrepreneurs when making decisions regarding waste management strategies. MDS is a statistical analysis tool that describes patterns of closeness in the form of similarity or resemblance. MDS can provide quantitative estimates of similarity between groups of items. MDS can transform consumer judgments of similarity or preference (e.g., preference for a store or brand) into distances represented in a multidimensional space. More formally, MDS refers to a set of statistical techniques that are used to reduce the complexity of datasets by providing a visual representation of the underlying relationships between groups (Hout *et al*., 2013). MDS is broad applications in many disciplines including the management of natural resources, marketing (Carroll and Green, 1997), political science, sociology (Russel and Bullock, 1985; Amato, 1990), and ecology (Kenkel and Orloci, 1986) among others. There are two advantages of MDS compared to other multivariate techniques. First, MDS analysis can be performed at the individual level by providing a perceptual map for multiple objects or subjects. However, multivariate MDS does not allow analysis at the individual level. Second, MDS allows the selection of dimensions without having to rigidly describe product attributes (Hout *et al*., 2013). The present study also provides information that may reduce economic costs and the price of microalgae-based biofuels. The objectives of the present study, in general, were to assess the sustainability of microalgae supply systems. Specifically, this study aimed to 1) determine the multidimensional sustainability index and status of microalgae production; 2) assess the sustainability index of each dimension of the sustainability index (socio-cultural, economic, ecological, and technological); 3) identify factors that affect microalgae production systems; and 4) determine the most dominant factor affecting microalgae production systems. A sustainability index for microalgae production systems may have utility as a reference for developing microalgae production systems that meet the needs of biorefinery for both current and future generations by managing factors that affect each dimension of the index, thereby improving methods of algal production. The present study was performed at the Research Center for Sustainable Production System and Life Cycle Assessment of the National Research and Innovation Agency, Indonesia in 2022.

MATERIALS AND METHODS

The present study was conducted at the Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, South Tangerang Regency, Banten Province, Indonesia.

Research materials

The present study evaluated the cultivation of *Chlorella sp*. with a bacterial consortium in POME in a 1 m^3 open raceway pond. Data were used to calculate the sustainability index of microalgae biomass production in Indonesia.

Study procedure

Researchers in the microalgae research community and the scientific judgment of experts were provided questionnaires regarding microalgae production. Data were processed and analyzed using the MDS method. MDS analysis was performed using Rapfish software (Pitcher and Preikshot, 2001). The present study analyzed four dimensions (social, economic, ecological, and technological) consisting of 47 attributes related to the environment, society, economy, and technology. Attributes in the

environmental dimension were efficiency of chemicals use, water use, harvesting process, pollution potential, utilization of CO_2 gas and generated waste, level of exploitation of natural resources, and land conservation rate. Attributes in the social dimension were education level, involvement of family members, business motivation, the potential for public unrest, potential job loss, and knowledge of environmental conservation. Attributes in the economy dimension were productivity of biomass, potential for increasing business scale, efficiency or transportation, and level of management production. Attributes in the technology dimension were biomass production system, management experience and skills, production facilities, technological improvement potential, and biodiesel production system.

Data analysis

For MDS, points were mapped such that the distance between objects was proportional to their similarity. The ordination or distance determination techniques used in MDS are based on Euclidian distance in n-space using Eq. 1 (Alder *et al*., 2000; Pitcher and Preikshot, 2001).

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

Where, configurations of objects or points in MDS are approximated by regressing Euclidian distance (d_{ij}) from point i to point j with point of origin (o_{ij}) using Eq. 2 (Alder *et al*., 2000).

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The ALSCAL algorithm is used for regression in the above equation. The ALSCAL method optimizes squared distance (squared distance = d_{ijk}) against squared data (point of origin = o_{ijk}), which in three dimensions (i, j, k) is termed S-Stress using Eq. 3 (Alder *et al*., 2000).

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

Where, the squared distance is Euclidian distance assigned a value using Eq. 4 (Alder *et al*., 2000).

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \quad (4)$$

The Rap-biomass ordination analysis of the sustainability of microalgae biomass production in Indonesia comprised a number of stages: 1) determination of microalgae biomass production sustainability attributes in Indonesia covering environmental, economic, social, and technology dimensions; 2) evaluation of each attribute on an ordinal scale (scoring) based on the sustainability criteria of each dimension; and 3) preparation of sustainability indices for microalgae biomass production. An ordinal scale was used to rank the sustainability attributes of each dimension from the least (0) to the greatest (3). Accordingly, the sustainability index was divided into four levels (Kavanagh and Pitcher, 2004); not sustainable (0%–25%), less sustainable (> 25%–50%), moderately sustainable (> 50%–75%), and sustainable (> 75%–100%). The sustainability levels of each dimension were also presented using a radar chart. The random errors for all dimensions were determined using the Monte Carlo approach. Outputs from the Monte Carlo and MDS analyses were compared, with a 95% degree of confidence indicating that the difference in value between the outcomes was 5%. The social, ecological, economic, and technological dimensions used in the present study of microalgae cultivation sustainability (Lam, 2016) are derived from known determinants of sustainability. Finally, a sensitivity analysis was performed to determine the variables with the greatest effect on the microalgae cultivation sustainability index. Several tests were used to determine data validity and the accuracy of the analysis. Stress values were calculated (standardized residual sum of a square), with stress values of 0.20 indicating 50% stress. Monte Carlo ordinated results were declared satisfactory if a narrow range of values was obtained. Previous studies using the MDS method are presented in Table 2.

RESULTS AND DISCUSSION

To determine the sustainability of the biorefinery process and identify related attributes, the sustainability index value was calculated using the MDS method. The dimensions of the MDS used in the present study were social, economic, environmental

Table 2: Previous studies using MDS analysis

No.	Title/topic of research	Dimensions of sustainability index	References
1	Palm oil-based bioenergy in Indonesia	Environmental, social, economic	(Papilo *et al.,* 2018)
2	Bioenergy policy: The biodiesel sustainability dilemma in Indonesia	Ecological, social, economic	(Dharmawan *et al.,* 2020)
3	Evaluating the sustainability of energy plantation forests in East Lombok District, Indonesia	Ecological, social, economic	(Narendra *et al*., 2019)
4	Evaluating the sustainability status of fisheries	Ecological, social, economic, ethical	(Pitcher and Preikshot 2001)
5	Assessing the potato farming index and the sustainability status of in Gowa	Ecological, social, economic, institutional	(Saidaa *et al.,* 2016)
6	Applying metric and nonmetric multidimensional scaling to ecological studies	Ecological	(Kenkel and Orloci, 1986)
7	Sustainable agricultural development	Ecological, social, economic, institutional	(Suardi *et al*., 2022)
8	Palm oil sustainable management	Social	(Dahliani and Maharani, 2018)

and technology. The data used for this calculation were obtained from questionnaire answers. The present also identified the attributes contributing to the sustainability of microalgae culture.

Index of sustainability

The attributes contributing to sustainability based on the scientific judgment of experts were used to determine the sustainability index for microalgae production. The determination of attributes should be specific and temporal (Pitcher and Preikshot, 2001). The attributes in the environmental, social, economy, and technology dimensions are presented in Table 3.

The attributes in the environmental dimension were efficiency of chemicals use, water use, harvesting process, pollution potential, utilization of CO_2 gas and generated waste, level of exploitation of natural resources, and land conservation rate. The attributes in the social dimension were education level, involvement of family members, business motivation, the potential for public unrest, potential job loss and, knowledge of environmental conservation. Attributes in the economy dimension were productivity of biomass, potential for increasing business scale, efficiency or transportation, and level of management production. Technology attributes consisted of biomass production system, management experience and skills, production facilities, technological improvement potential, and biodiesel production system. To determine the sustainability of the biorefinery process used in biomass microalgae production, the attributes in each dimension were formulated into a sheet questionnaire and provided to relevant experts to obtain their scientific judgment. Furthermore, the results of the experts' assessments were analyzed using the MDS method in Rapfish software. The calculated sustainability indices for each dimension are presented in Table 4.

The conditions for sustainable microalgae cultivation are determined by environmental carrying capacity, production input availability, production processes, product processing, marketing of microalgae, and the role of related institutions. The results of our MDS analysis of sustainable microalgae cultivation are presented in Fig. 1. As measures of the validity and accuracy, we observed a stress value of 0.14 (stress 50%) and almost identical results from the Monte Carlo test between dimensions, i.e.,. the technological attribute (73.67%) and the economic attribute (70.99%).

Environmental dimension

The sustainability index for the environmental dimension was 67.30%, with the ability of microalgae to utilize industrial CO_2 being the most impactful attribute (Table 4). On the other hand, the most

Table 3: List of dimensions and their attributes

Environmental	Social	Economy	Technology
1. Efficiency level in the use of materials (biodegradable) for the manufacture of biomass production reactors 2. Efficiency level in the use of materials (non-biodegradable) for the manufacture of biomass production reactors 3. Efficiency level in the use of chemicals for media/fertilizers with POME 4. Efficiency level of fuel use for harvesting and drying biomass 5. Water use efficiency (biomass) 6. Potential for air pollution (biomass) 7. Potential for water pollution (biomass) 8. Utilization of CO_2 emissions from industry 9. Utilization of generated waste (biomass) 10. Level of exploitation of natural resources for reactor construction 11. Land conservation rate 12. Efficiency level in the use of basic materials (microalgae biomass) for biodiesel production 13. Efficiency level of use of chemicals (biodiesel) 14. Efficiency level of fuel use (biodiesel) 15. Water use efficiency (biodiesel) 16. Potential for air pollution (biodiesel) 17. Potential for water pollution (biodiesel) 18. Utilization of generated waste (biodiesel)	19. Officer education level 20. Involvement of family members in household scale microalgae biomass production 21. Business motivation 22. The potential for public unrest due to the production process 23. Potential job loss 24. Level of knowledge on environmental conservation and restoration 25. Officer education level (biodiesel) 26. Involvement of family members in household-scale microalgae biodiesel production 27. Business motivation (biodiesel) 28. The potential for public unrest due to the boidiesel production process 29. Potential job loss (biodiesel)	30. The productivity level of microalgae biomass with POME 31. Production management level (biomass) 32. Potential for increasing business scale (biomass) 33. Contribution to improving food welfare (biomass) 34. Transport Efficiency Level (biomass) 35. The productivity level of biodiesel 36. Production management level (biodiesel) 37. Potential for increasing business scale (biodiesel) 38. Contribution to increase in fuel/biodiesel substitution 39. Transport Efficiency Level (biodiesel)	40. Biomass production system 41. Management experience and skills (biomass) 42. Availability of production facilities (biomass) 43. Technological improvement potential (biomass) 44. Biodiesel production system 45. Management experience and skills (biodiesel) 46. Availability of production facilities (biodiesel) 47. Technological improvement potential (biodiesel)

impactful environmental attribute was utilization of generated waste. During cultivation of microalgae, it is conceivable to put through wastewater treatment and CO_2 sources (Handayani *et al.,* 2020). Microalgae can grow in any medium that contains the nutrients required for their growth. Nutrients required for

Table 4: Sustainability index results for environmental, social, economy and technology dimensions with data quality indices

Dimension	Index (%)	Stress	R^2(SQR)
Environmental	67.30	0.13	0.95
Social	82.17	0.13	0.95
Economy	70.99	0.14	0.95
Technology	73.67	0.14	0.95
Average	73.53	0.14	0.95

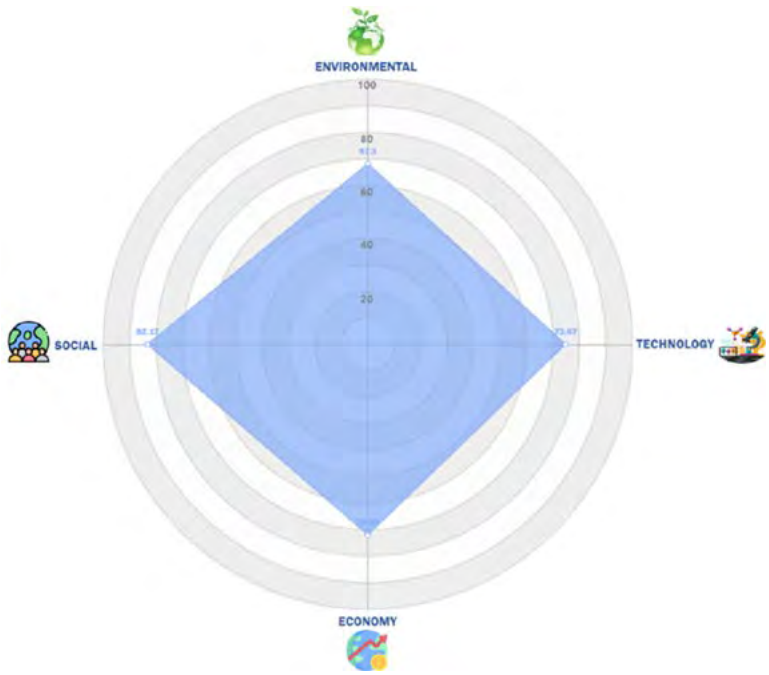

Fig. 1: Sustainability status of microalgae biomass production for biorefinery

microalgae growth include nitrogen, phosphorus, and carbon, which are commonly found in POME ponds (Zullaikah *et al*., 2019). In addition to nutrients found in POME, the growth rate and lipid content of microalgae can be influenced by light intensity, glucose concentration, and carbon dioxide concentration (Chew *et al*., 2018). Many studies have indicated that POME is an ideal medium for microalgae cultivation as it contains all nutrients required for microalgae growth in open ponds with sufficient sunlight. The POME constituents and conditions that are required for microalgae growth are presented in Table 5.

A previous study stated that the potential environmental benefits of using CO_2 from flue gas and wastewater from microalgae cultures for the generation of biofuels (Collotta *et al*., 2018). Before wastewater is released into waterways, it must first be treated to remove phosphate and nitrate. The utilization of CO_2 emissions from power plants to support algae cultivation may contribute to reductions in CO_2 emissions into the environment. Of note, the carbon footprint of algae-based biodiesel is lower than that of conventional diesel (Naeini *et al*., 2020). Microalgae consume CO_2, which is discharged into the atmosphere in power plant exhaust gases (Handayani *et al*., 2018). Accordingly, carbon taxes, carbon trading, and carbon subsidies may have a significant impact on the viability of algal biofuels in the future. The ability of microalgae to absorb and capture CO_2 should be considered when developing policies aimed at increasing CO_2 capture, particularly from power plants. The utilization of industrial CO_2 therefore had the greatest leverage of all environmental attributes included in the present study.

Table 5: POME constituents and conditions (Sasongko *et al*., 2014)

Parameters		Cooling pond (Inlet)	Aerobic pond (Outlet)
Total COD	(g/L)	40–90	0.35–1.3*
Total BOD	(g/L)	15–30	0.1–0.7*
TSS	(g/L)	20–40	0.70
TDS	(g/L)	15–30	
VSS	(g/L)	15–35	
Total Carbohydrate	(g/L)	29–45	
Total Proteins	(g/L)	17–32	
Total Lipids	(g/L)	15–23	
Total N	(g/L)	0.149*	0.456–0.750*
NH_3+N	(g/L)	0.050*	0.0342
Total P (PO_4^+)	(g/L)	0.315*	0.068–0.018*
K	(g/L)	1–2.5	0.110–0.924
Mg	(g/L)	0.25–1	0.017–0.0152
Temperature (°C)		70–80	30–40
pH		4–5	7

*Sample measured at PTPN, Riau.

The metabolism of CO_2 by microalgae represents a potential method of disposing of POME waste produced by palm oil plantations. Compared to terrestrial oil-producing plants, microalgae produce 30 times more oil per unit area of land (Hadiyanto and Nur, 2012a). This difference is attributable to microalgae generally being more efficient in converting solar energy despite the similar photosynthesis mechanisms between microalgae and higher plants. Microalgae have a simplified cellular structure that allows greater access to water, CO_2 and other nutrients (Sheehan *et al*., 1998). Moreover, nitrogen and phosphorus required for cultivation of microalgae can be obtained from wastewater effluent. Wastewater effluents such as POME may provide an appropriate environment for microalgae growth (Cantrell *et. al*., 2008). Biological processing of POME involving microalgae is a considered a better method than anaerobic digestion as microalgae consume organic substances as nutrients to produce biomass as an energy source and reduce the harmful effects of POME on the environment (Nurhayati and Basuni, 2013). The biotreatment of POME using microalgae is particularly beneficial for palm oil manufacturers (Rani *et al*., 2015) as the process is environmentally and economically friendly (Chai *et al*., 2021). Other benefits of using microalgae usage include the absorption of CO_2 from the atmosphere and release of oxygen (Francisco *et al*., 2010). Utilization of wastewater in an integrated manner and renewable bioenergy production are added benefits that may be profitable for palm oil industries (Ahmad *et. al*., 2016). The cost of bioenergy production remains higher than the extraction of conventional fuel sources (Kamyab *et.al*., 2017), particularly for lipid extraction (Lee *et al*., 2021). However, integration of biofuel production into biorefinery pathways may increase the recovery of value-added products (Chia *et. al*., 2018).

Social dimension

Social sustainability can be achieved through the implementation of regulation to reduce negative impacts and promote family-run businesses. Among the attributes in the social dimension, involvement of family members in the household had the highest score and business motivation (biodiesel) had the second highest score. In family-run companies, many employees are family members and are willing to provide the company with their own resources, thereby reducing the financial burden on the company. The organization of family-owned companies can also allow managers to focus on managing the company. The present analysis found a sustainability index value of 82.17% for the social dimension, which this indicates that the social impacts of microalgae production are quite sustainable. The social factors identified as impacting on biomass production systems were land ownership rights, local resource management, and labor rights. Social sustainability of microalgae biomass production is influenced by land ownership rights and promotes reforesting. Family member involvement in family-run microalgae biodiesel production had a significant impact on the sustainability status of microalgae cultivation. This

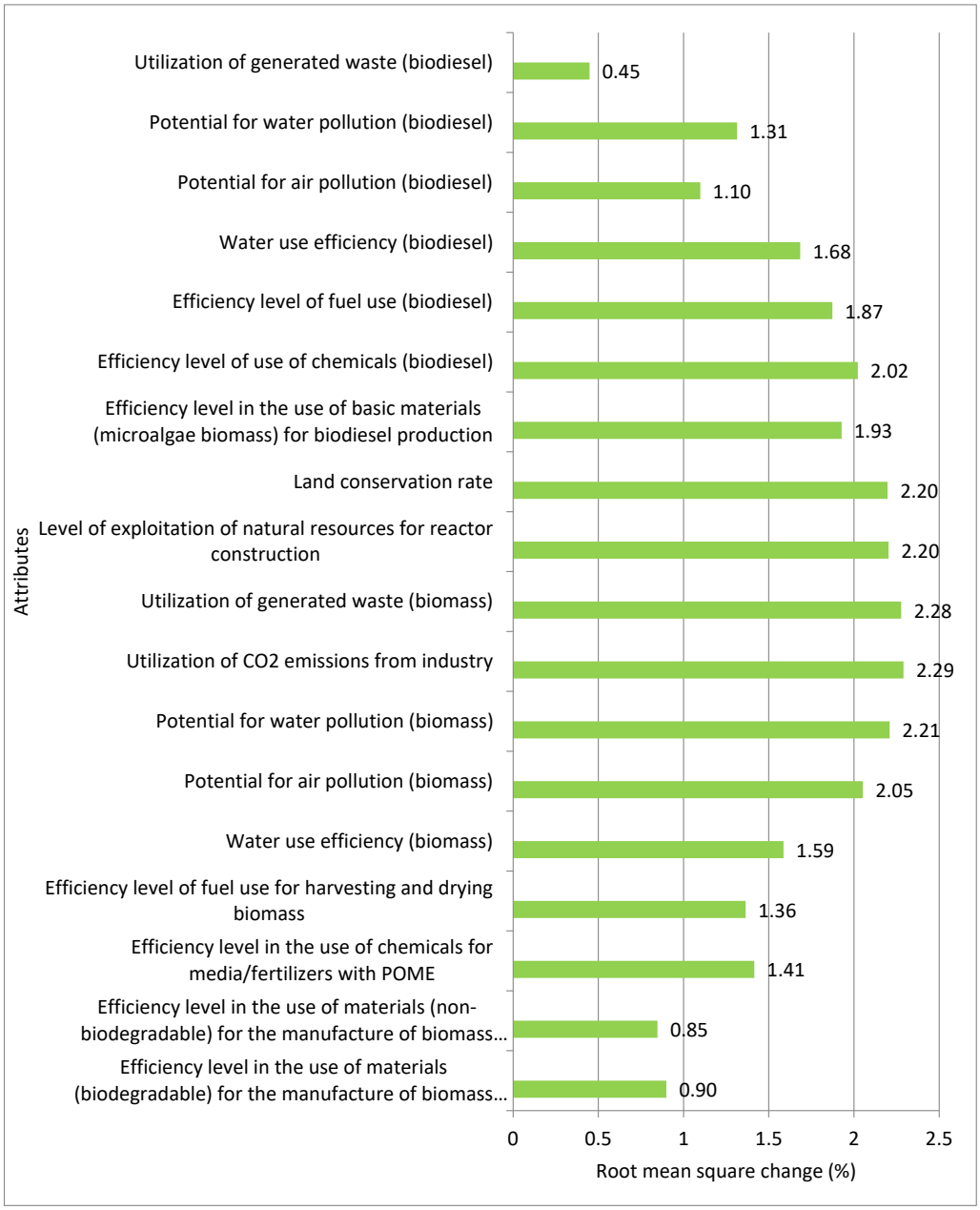

Fig. 2: Leverage of environmental attributes

result corroborates previous research demonstrating that microalgae photobioreactors (PBR) are typically used in low and middle-income countries (Osama *et. al*., 2021).

The management of local common property resources such as shared land, community forest, rivers and riverbeds, and dredging grounds also influences social sustainability. The approval of proposals for micro algae biomass production by management was also particularly important as this allows businesses to be supported by local property management in times of need. Microalgal biomass production contributes to job creation and rural prosperity by increasing the flow of capital, fertilizer,

infrastructure, and technology into the agricultural sector, thereby creating jobs, increasing wages, and increasing self-sufficiency in terms of access to electricity and portable pumps. Water pumping without causing adverse impacts is another factor contributing to the social sustainability of microalgal biomass production (Culaba *et al*., 2020). The above factors have been shown to be linked through circular reasoning (Levidow, 2013).

Economic dimension

The sustainability index of the economy dimension was 70.99%, with production management level and the productivity level of biodiesel found to have the greatest leverage on the sustainability of microalgae cultivation (Fig. 4).

The productivity of biodiesel production relies on the availability of capital, people, and technology. In micro-scale production, productivity standards are used to assess the efficiency of machines, factories, companies, systems, or people in converting inputs into desired outputs. In producing biodiesel from microalgae, the level of productivity determines sustainability, particularly in terms of selecting and acquiring raw materials that meet the specification required for biodiesel production. The level of biodiesel production management also affects sustainability. Production management includes planning, organizing, directing, and effectively controlling production. Production management acts to coordinate activities to achieve business goals. Accordingly, production proceeds in accordance with previous planning. The attribute "potential for business scale-up" had the third highest leverage on the sustainability of biodiesel production in the present study. This finding may be attributable to long-term costs, where average production costs are reduced as business size increases (Irawan and Hutabarat, 2016). Planning businesses at large scale may reduce the need for future expansion (Hadiyanto *et al*., 2012b).

Technological dimension

The present analysis found that the technology dimension had a relatively high sustainability index value of 73.67%. This indicates that the technological impacts of microalgae production are quite sustainable (Table 4). Management experience and skills in biodiesel production had the greatest impact on sustainability. The availability of biomass and biodiesel production facilities was also identified as an important factor

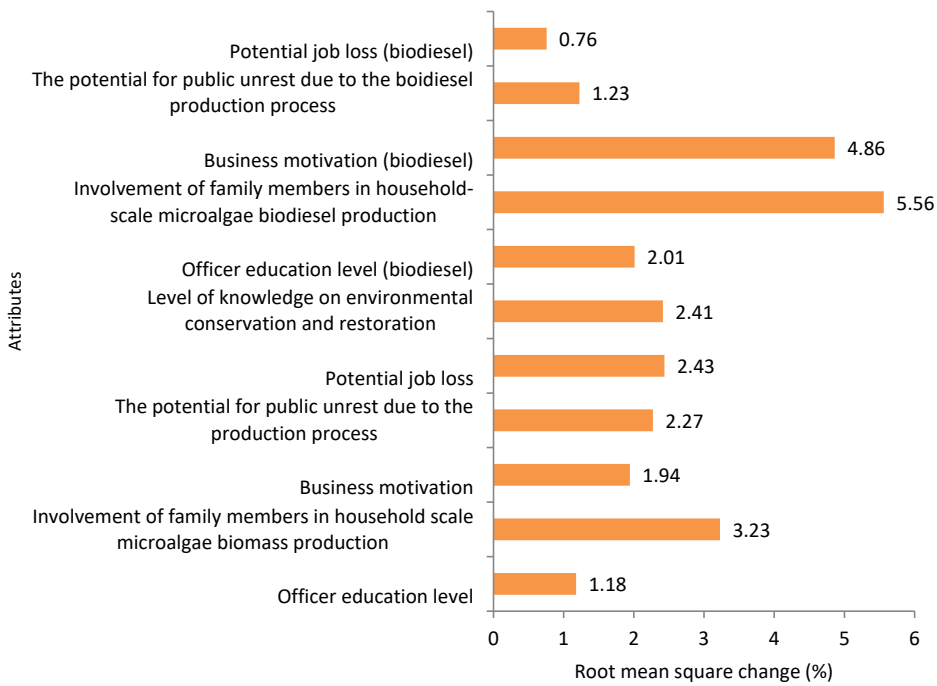

Fig. 3: Leverage of social attributes

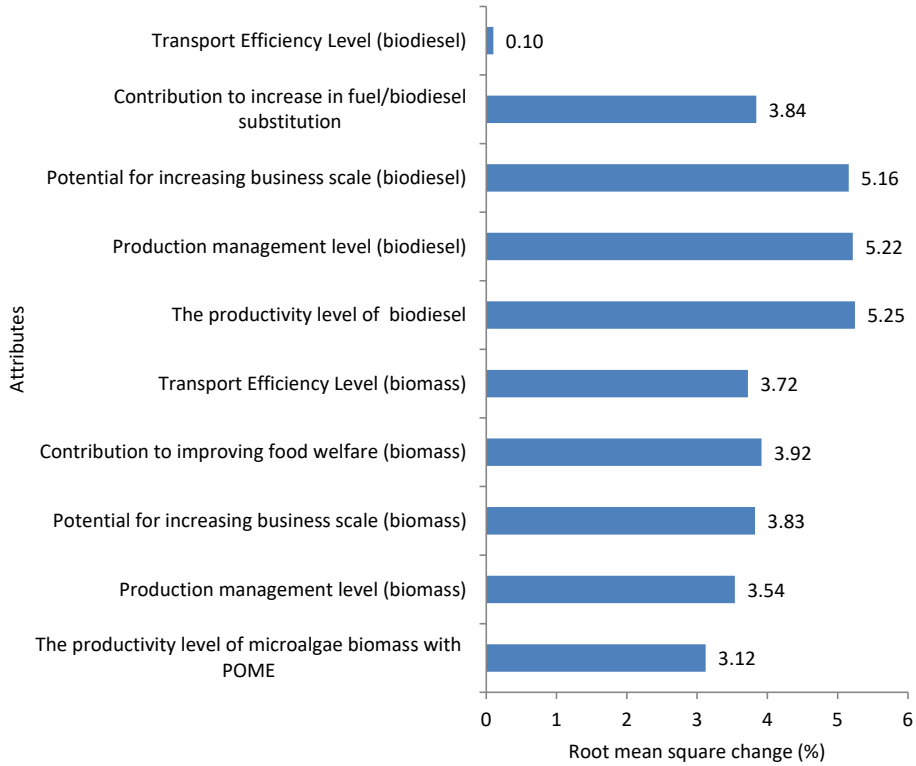

Fig. 4: Leverage of economic attributes

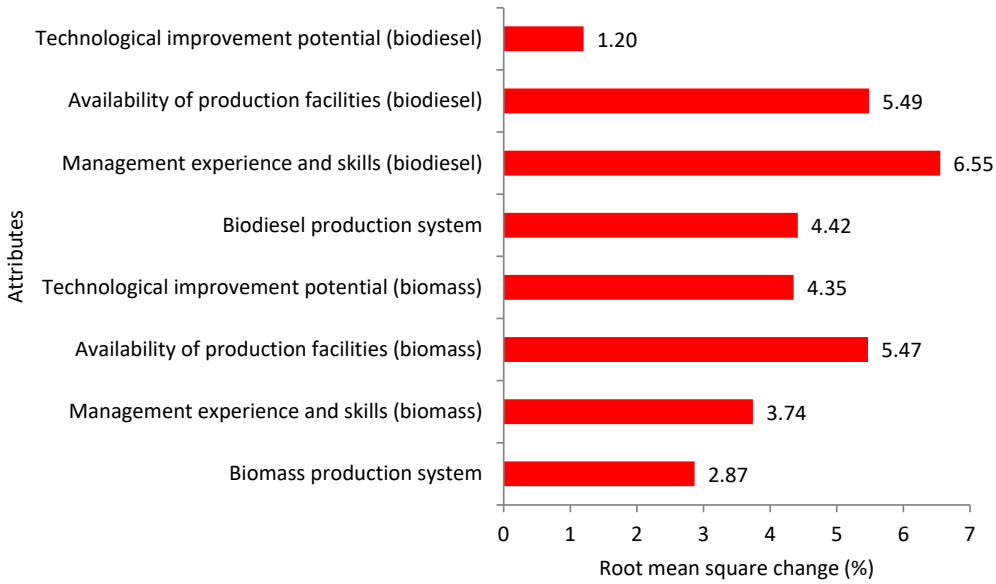

Fig. 5: Leverage of technology attributes

which may have a positive effect on employment opportunities for the surrounding community involved in production. The attribute of management experience and skill had the greatest leverage on the sustainability of microalgae cultivation (Fig. 5). These findings are in line with a report by Responsible Seafood in 2022 suggesting operators of an aquaculture hatchery should consider versatile microalgae production.

The analysis of the eight attributes in the technology dimension demonstrated that management experience and skills in biodiesel production had the greatest leverage on the sustainability index value. The sustainability index value provides information of the sustainability of biofuel production from microalgae biomass and the feasibility of increasing biodiesel production from microalgae in the future. However, the slow speed of technological innovation for scaling-up biodiesel production from microalgae makes it uneconomical for commercial-scale investment compared to the production of biodiesel from other feed stocks. Companies may cease to be viable without sufficient technological innovation. Increasing cooperation between companies and research institutions is important for increasing the development of technologies. Innovation roadmaps utilizing public funds for research development may also lead to the creation of new businesses. Management experience and skills in biodiesel production provide novel ideas that require implementation for commercial-scale production. The short-term outlook for microalgae biodiesel appears bleak; however, aviation technology may contribute to future development programs for biodiesel production (Patnaik and Mallick, 2021). The most critical issues to be addressed by innovations in microalgae technology are increasing growth rate and productivity while minimizing land conversion and consumption (Khan *et. al*., 2018). As microalgae biorefinery becomes increasingly important, there is a greater need for the development of more advanced technologies in the field of biorefinery and wastewater management (Chowdury *et. al*., 2020). Biological processing of palm oil liquid waste using microalgae helps preserve the environment in addition to being very profitable for producers (Bala *et. al*., 2014). Utilization of microalgae reduces the pollutant content of POME, removes CO_2 from the atmosphere, and produces O_2, which have beneficial effects on the environment (Nur and Buma, 2019).

Future prospects for microalgae production using POME

South East Asia is the region with the highest palm oil production worldwide. South East Asia's coconut palm oil (CPO) production accounts for 88.6% of global production at 54.38 million tons, rising from 40.33 to 48.12 million tons between 2010 and 2013 (FAOSTAT, 2016). Within this region, Indonesia is currently the leading producer of CPO, followed by Malaysia and Thailand. CPO production in Indonesia increased by 30.14% between 2010 and 2014. Indonesia's palm oil industry continues to grow and now has the highest CPO production worldwide at 32 million tons, accounting for approximately 46.6% of total CPO production worldwide. Global demand for CPO continue to increase and was estimated to be 95.7 million tons in 2020 (Low *et al*., 2021). The Central Bureau of Statistics noted that Indonesia's oil palm production has substantially increased in the past five years. In 2019, production reached 48.42 million tons, an increase of 12.92% from the previous year. Palm oil production continued to increase from 31.07 million tons in 2015 to 31.49 million tons a year later (BPS, 2020). The greatest increase was between 2017 and 2018 where production increased from 34.94 million tons to 42.88 million tons, an increase of approximately 22.72% (Annur, 2020). According to recent information on oil palm production, the South East Asian region faces serious environmental issues. Large amounts of POME wastewater are generated by the wet processing system, which may be harmful to the environment. Different cultivation modes, careful species selection, and different conditions can improve the growth, biomass yield, and productivity of several value-added products from microalgae grown in wastewater. The ability of microalgae to remove unwanted products determines their performance in treating POME. Many undesirable products are present in POME wastewater that are also pollutants that can harm the environment and require treatment to prevent pollution by POME. Microalgae can remove pollutants, thereby providing a cost-effective and long-term solution for POME treatment (Kamarudin *et al.*, 2015). There are numerous advantages to using microalgae to treat POME, including reduced pollutant content in wastewater. This technology may also have applications in other sectors. Microalgae grown in POME can be used as a feedstock for the production of biofuels as microalgae have a high biomass yield and can be cultured on smaller land areas that are not suitable for food production (Benedetti *et al*., 2018).

CONCLUSIONS

The data validity and accuracy in the present study had a stress value of approximately 0.14 (stress 50%). In addition, the results of Monte Carlo ordination demonstrated that technological and economical attributes had similar values of 73.67% and 70.99%, respectively. The ability of microalgae to absorb and capture CO_2 can inform future policies for CO_2 capture, particularly from power plants. The present study found that increasing usage of industrial CO_2 had the highest leverage on the environmental impacts of microalgae production. The social sustainability of microalgae biomass production was influenced by land ownership rights allowing successful reforestation. Involvement of family members in household microalgae biodiesel production had a significant influence on the sustainability of microalgae cultivation, with management of local common property resources such as shared land, community forest, rivers and riverbeds, and threshing grounds also contributing. Approval of proposals for micro algae biomass production was also particularly important by allowing businesses to run at the cost of local property management in times of need. Business management allows coordination of activities to achieve business goals. The use of innovation roadmaps for utilizing public funds for research development may lead to the establishment of new businesses. Management experience and skills on biodiesel production may provide novel ideas for commercial-scale production. The average sustainability index value in the present study was 73.53%, indicating microalgae production is sustainable. This finding indicates the treatment of POME with a combination of microalgae and bacterial consortia represents a potentially sustainable method of POME processing. There is a need for continued research on microalgae biomass to improve yields of value-added products using optimal, sustainable, and economical cultivation systems. The concept of sustainable POME processing using microalgae proposed in the present study appears to have high feasibility for implementation in Indonesia.

RECOMMENDATIONS

Research on POME processing using microalgae remains in its infancy. As a result, combining a microalgal system with traditional POME treatment appears promising and feasible. Given its potential as a source of bioenergy, the integration of microalgal culture into currently used POME treatment systems has become much more feasible. To maximize the socio-economic benefit of algae-derived biodiesel development, areas with a high socio-economic impact multiplier should be chosen while taking into account regional climate, marginal land, and socio-economic factors. As a promising and sustainable source of biofuel that can help reduce atmospheric greenhouse gas emissions, microalgal biomass has been demonstrated to be one of the most efficient and environmentally friendly alternative energy sources. The implementation of a biorefinery approach with the recovery of many products from a single operational process provides an opportunity for the development of microalgal biomass-based technologies. A biorefinery platform based on the transformation of microalgal biomass into fuels, food, dietary and feed supplements, fertilizers, and pharmaceuticals represents one of the most promising methods for achieving this goal according to the biorefinery complexity index.

AUTHOR CONTRIBUTIONS

T. Handayani performed the literature review, designed the study, supervised the experimental work, and drafted the manuscript. A.D. Santoso performed the literature review, performed experimental work, and drafted and prepared the manuscript. J. Hariyanti supported experimental and administrative work and provided technical and material assistance. Kusrestuwardani supported experimental work and data acquisition. D. Pinardi performed data analysis and interpretation. H. Apriyanto performed statistical analysis. A.I. Sitomurni performed manuscript preparation and critical revisions. I.N. Djarot performed critical revisions and supervised manuscript preparation. N. Widyastuti supervised all experiments and manuscript preparation.

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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

%	Percent
ASCAL	Alternating least-squares algorithm
BOD	Biological oxygen demand
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CPO	Coconut palm oil
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
Fe	Iron
K	Kalium
MDS	Multidimensional scaling
Mg	Magnesium
mg/L	Miligram per liter
N	Nitrogen
NH_3	Amonia
O_{ij}	Point of origin
O_2	Oxygen
pH	Potencial of hydrogen
PBR	Photobioreactor
PO_4^+	Ortofosfat
P-rich	Phosphate-rich
POME	Palm oil mill effluent
PTPN	Perseroan terbatas perkebunan nusantara, an Indonesian state-owned company engaged in the plantation sector
Rapfish	Rapid appraisal for fisheries
RMS	Root mean square
SQR	Structured query reporter
TDS	Total dissolved solid
TSS	Total suspended solid
VSS	Volatile suspended solid

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CASE STUDY

Green transformational and transactional leadership in fostering green creativity among university students

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ABSTRACT

BACKGROUND AND OBJECTIVES: The current study investigates green transactional leadership for the first time in order to understand leader-follower relations in studying green behavior in higher education institutions. The aim of this study is to investigate the dynamic relationship between green transformational leadership, green transactional leadership and green creativity that are mediated by green intrinsic motivation.

METHODS: This study used adapted constructs from previous environmental research as well as a newly-developed green transactional leadership construct. Responses were obtained from university students working on their final-year projects. In order to evaluate the model, partial least squares structural equation modeling using Measurement model assessment was used to validate the structural and measurement model.

FINDINGS: Findings indicate that green intrinsic motivation significantly influences the relationship between green transformational leadership and green creativity (Beta=0.321; t=3.129), as well as green transactional leadership and green creativity (Beta=0.114; t=2.322). However, green transformational leadership is a stronger predictor in comparison to green transactional leadership in nurturing green creativity among students to provide viable solutions to existing products/processes. The R2 or contribution given by green transformational leadership and green transactional leadership on green creativity was 45.7 percent while the contribution of green transformational leadership, green transactional leadership and green creativity on green intrinsic motivation was 57.7 percent.

CONCLUSION: Policy makers must focus their attention on promoting green transactional and transformational leadership that will directly enhance students' motivation to promote the green creativity through innovative product/service model innovation.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
38	1	6

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INTRODUCTION

With the rapid growth, industrialization and economic development across the globe, the increase in environmental pollution has resulted in the need to utilize natural resources more efficiently by promoting sustainable development (Al-Dailami *et al.*, 2022). For this purpose, the community and companies need to unite to reduce the negative impact of industrial development through innovative, green and eco-friendly (Kamyaba *et al.*, 2019) processes e.g., microalgal biotechnology, toward sustainable development (Kamyaba et al., 2019). Many research studies focused on sustainable environmental objectives that can be achieved by promoting green creativity (GCT) approaches in production (Zameer *et al.,* 2020). GCT is the concept depicted in product/service characteristics through embedding and incorporating eco-friendly and resource-efficient attributes and/or processes. GCT can be evident as a catalyst in attaining competitive advantage through solving global ecological, contamination and other environmental issues. It is a common practice among business circles that sustainable development can be promoted by aligning human development with environmental concerns (Arslan *et al.,* 2022). Promoting GCT among all employees is the prime and utmost responsibility of the top management (Arici and Uysal, 2022). If organizational leaders possess the attitude for promoting environmental sustainability through thier enlightened vision. As a result, the outcome will be nurturing a workforce imbued with environmentally-friendly perspectives and approaches . Leadership therefore is the key approach in promoting creativity among followers. To this end, transformational leadership involves supervision that promotes creativity among workers through a stimulating and group goal behavior. Green transformational leadership (GTRF) stimulates employees to achieve organizational goals through the innovative approach of solving environmental issues and fostering a challenging culture to express their highest level of creativity (Li *et al.,* 2020). The previous literature mainly focused on studying GCT at the organizational level (Jia *et al*., 2018; Riva *et al.,* 2021), however in order to understand the concept of GCT, it is exigent to investigate it from an individual perspective, because organizational green creativity can be better understood from the point of view of individuals *vis-a-vis* leaders and employees (Riva *et al.,* 2021). The existing literature indicates the need to foster internal mechanisms to promote GCT because of the external pressure exerted by various stakeholders (Zhang *et al.,* 2020). In order to promote the green agenda in organisations, employees' intrinsic motivation is the most important aspect for sustainable development (Faraz *et al*., 2021; Shafi *et al.,* 2020). Employees' green intrinsic motivation (GIM) is the approach in which employees are motivated to apply the latest tools/ techniques to provide safeguards to nature without any financial benefits. GIM is the operative attitude related to one's internal locus of control and caring behavior for the natural environment due to the employee's actions associated with the production processes (Li *et al.,* 2020). Employees' internal feelings of satisfaction with safeguarding nature and promoting green products to conserve and protect the environment from damages caused by individuals or organizational actions (Joshi and Dhar, 2020). Employees' GIM is the driving force to regulate the behavior of employees while performing their jobs in the organization and working on innovative solutions for their existing product design that will minimise its impact on the natural environment (Ali *et al.,* 2020). Infusing the feeling of motivation and fostering a culture of innovation and creativity mainly depends on the active leadership role in the organization. In this regard, a number of research studies (Du and Yan, 2022; Zhang *et al.,* 2020; Farrukh *et al.,* 2022) investigated the significant contribution of GTRF in promoting eco-friendly and sustainability approaches among the employees. While the GTRF has seen significant interest in the environmental sustainability literature, green transactional leadership (GTRS) which emphasises the attainment of results, conformity to structures within the organisation and performance measurement to a set of established metrics has not been studied in depth (Bass and Avolio, 1993). GTRS involves leaders possessing formal authority and responsibility for maintaining routing and performance by using rewards and punishments among the employees in the organisation (Bass and Avolio, 1993). GIM is cultivated through the formation of a shared vision and the development of a professional attitude by the top management (Rizvi and Garg, 2020). In this regard, this unique management style is considered as the most appropriate style that develops the motivation of employees to promote creativity for a sustainable environment (Li *et al.,* 2020). In behavioral research, GTRF is considered as a vital force in relation to employees commitment, satisfaction and motivation

(Çop *et al.,* 2021). Results from previous studies (Li *et al.,* 2020) indicate that GTRF plays an important role in shaping employees' creativity, which is ultimately enhanced by the intrinsic-extrinsic motivation mechanism. A study by Li *et al.* (2020) found that employees' GIM is significantly associated with GTRF and employees green creativity among the Chinese manufacturing sector. Similar results are also quoted by (Faraz *et al.,* 2021) from Pakistan's energy sector. It was deduced that employees' GIM will enhance their self-efficacy to promote an eco-friendly environment. Similarly, the result from the study of Arici and Uysal, (2022) using a meta-analysis depict that most of the previous research studies investigated green transformational leadership with a focus on employees' GCT in various manufacturing environments. According to Rehman and Yaqub, (2021), GTFL is a significant contributor towards environmental concerns while focusing on the greening aspect of the hospitality sector's operations during the COVID-19 pandemic. Most of the studies (Zhang *et al.,* 2020; Farrukh *et al.,* 2022; Masum and Pal., 2020; Abu-Qdais *et al.,* 2020) investigated the GIM of employees through the lens of transformational leadership and the concept of transactional leadership is somewhat absent in organizational behavior and environmental research. It is worth mentioning that GTRF was measured using a six-item scale developed by Chen and Chang, (2013), while the Bass Model of Leadership assessed the concept of transformational leadership with 26 items. Similarly, a large number of research studies compared the Bass Model of Leadership approach from the lense of transformational and transactional leadership. Vargas-Hernandez, (2022) opined that GTRF is a major factor in the attainment of sustainable development goal in organisations and therefore requires adequate attention. However, the concept of GTRF has not been investigated to date. Hence, the major aim of the study is to investigate the concept of green transactional leadership for the first time in behavioral and environmental management domain among university students who are working on their final year project. The current study tries to investigate the impact of teaching facultys' green transformational and transactional approaches to enhance student's green creativity while working on their final year project. However, students' GIM is used as a possible mediator in the leader-member relationship. This study builds on the leader approach to enhance creativity of student through the inculcation of motivation among students to contribute towards a clean and green environment. It is also the objective of the study to investigate the mediating role of students' GIM on GTRS and GTRF in the Pakistan higher education sector to promote the green product development concept through students' GCT. The green product development concept is based on developing a new prototype, that students try to develop during the final year project which involves efficient use of natural resources and reducing the harmful effect of rapid industrialization. Across the globe, students from various specializations work on specific issues and then present viable solutions to the problem through prototype design for new product design or process reengineering. This study was conducted in Pakistan during 2021 and 2022.

MATERIALS AND METHODS

The current study population consists of university students working on their final year project from various public and private sector universities in the Khyber Pakhtoonkhwa region of Pakistan. This study received ethical approval clearance (Reference no: EA3282021) from Multimedia University to commence data collection from the respondents. The sample consisted of 109 students from the University of Science and Technology Bannu, Gomal University, Karak University, CECOS University, Peshawar University and the University of Engineering and Technology. The selection of the students were based on a purposive sampling procedure with only students that are working on environmentally-friendly solutions through modification/redesign and innovative solutions to existing product/process design were selected for this study. Written informed consent was obtained from the respondents before they proceeded to complete the survey in which its participation was voluntary. This study applied the structural equation modeling technique using the Smart PLS software because the model consists of a mediating variable and a newly developed construct for GTRS. Smart PLS has been highly recommended in the case of small samples as in the current study simple size is also small. With its robust nature and predictive power for instrument reliability and validity (Hair *et al.,* 2017) Smart PLS is the choice of researchers.

Measurement

GIM was measured using a 6-item scale by adapting the construct of Li *et al.,* (2020). On the other hand,

GCT was measured with a 6-item scale adopted from Chen and Chang, (2013). As the previous construct of GTRS consisted of only 6 items (Chen and Chang, 2013), while the concept of GTRF composed of 5 attributes which are namely articulating vision, intelectual stimulation, individualized consideration, group goal and inspirational motivation (Bass and Avolio, 1993) while Podsakoff *et al.* (1990) promulgated the attribute of leadership that is composed of articulating a vision, providing an appropriate model, fostering the acceptance of group goals, high performance expectations, individualized support, and intellectual stimulation. Hence, the newly-developed ítems for GTRF which are GTRF 7-9 are developed based on the work of Bass and Avolio, (1993). On the other hand, the GTRS construct was newly developed for this study in light of the recommendations of previous researchers such as Bass and Avolio, (1993) to incorporate elements of rewards and punishment. The details of the indicators/ ítems used for all the variables are presented in Table 2 for reference. The questionnaire consists of various adapted versions of constructs adopted from previous research and newly-developed items for GTRS and GTRF as discussed in detail (Table 1). GTRF is a 9-item construct that was adopted from Chen and Chang, (2013) with 3 new items added from the theoretical discussion by Bass and Avolio, (1993) to provide better clarity to the GTRF concept.

RESULTS AND DISCUSSION

Characteristics of the respondents

The findings indicate that most of the respondents belong to University of Science and Technology Bannu. Most of the students belong to the 21 years and above age group and are studying for their 16 year Bachelor's degree. Results about specialization of studies indicate that the highest percentage of students belongs to management sciences followed by enginering. The respondents indicated that 39 percent (%) are engaged in final prototype development while 27% are in the conceptual development stage.

Measurement model assessment (Smart PLS)

SmartPLS 4 was used to measure the model assessment that consists of composite reliability (CR) which measures the internal consistency, factor loading for each item of the construct, distinctive reliability for each indicator and average extracted variance (AVE) to measure convergent validity and discriminant validity (Hair *et al.,* 2017). In the current study, each construct is reflective in nature; hence partial least square structural equation modeling technique is the appropriate procedure to understand the nature of various adopted constructs (Hair *et al.,* 2017). In this regard, factor loadings for all the items are higher than the threshold level of 0.60 as recommended by Legate *et al.,* (2021). The assessment results of the measurement model in Table 2 indicate the items measuring the variables together with the factor loadings and AVE obtained. As presented in Fig. 1, the highest factor loading in transformational leadership belongs to item GTF2, while green creativity's highest loading is for item GCT3, and the newly-developed green transactional leadership's highest loading belongs to item GTRS2. Although the factor loading of green intrinsic motivation items GIM1 (0.699) and GIM5 (0.681) are lower than 0.7, the overall model assessment based on AVE is good, therefore not creating any problem for further analysis. Hence, these two GIM ítems were retained. Item (question) loading on the relevant factors (construct) indicate the correlation between the ítems or questions and its relevant factors. Factor loading values for the items reported are within the range of -1 to 1. The results in Table 2 indicate that that the item loadings are higher than 0.6 and loaded well on their respective factors. The item loadings in Smart PLS are calculated based on algorithms during the measurement model assessment stage, hence if the values satisfy the assumptions as recommended by Hair *et al.,* (2017) and Legate *et al.,* (2021), the statistical model is therefore ready for further bootstrap analysis to determine the path relationships. Table 2 also indicate that the composite reliability (CR) values are higher than 0.60 and the AVE

Table 1: Measurement method (questionnaire and scaling)

Variable	Indicators	Reference
Green Transformational Leadership (GTRF)	1-6	Chen and Chang, (2013)
	7-9	Newly developed based on Bass and Avolio, (1993)
Green Transactional Leadership (GTRS)	1-4	Newly developed based on Bass and Avolio, (1993)
Green Intrinsic Motivation (GIM)	1-7	Li *et al*., (2020)
Green Creativity (GCT)	1-6	Chen and Chang, (2013); Li *et al*., (2020)

Table 2: Assessment result of measurement model

Construct		Indicator	Loading factor	Composite reliability	Cronbach alpha	AVE
GTRF	GTRF1	The project leader inspires the team with his/her environmental plans for adding features related to new product/services development.	0.804	0.891	0.914	0.592
	GTRF2	The project leader provides a clear environmental vision for adding features related to new product/services development.	0.854			
	GTRF3	The project leader always guides the team to work together for the same environmental goals while developing new product/services.	0.768			
	GTRF4	The project leader always encourages the team to achieve the environmental goals through adding features related to green product/services development.	0.802			
	GTRF5	The project leader always acts with considering environmental beliefs for the development of any product/services prototypes.	0.721			
	GTRF6	The project leader always encourages the team to add green ideas during product/services development.	0.709			
	GTRF7	The project leader always inspires the team to apply latest technology with minimum hazard for environment.	0.751			
	GTRF8	The project leader always envisions the team to think environmental issue before designing any product/service model.	0.743			
	GTRF9	The project leader always focuses on group goal behavior for sustainable environment.	0.756			
GIM	GIM1	Coming up with new green ideas for new product/services design is always enjoyable.	0.699	0.944	0.929	0.709
	GIM2	Solving environmental issues through new product/services model is always enjoyable.	0.899			
	GIM3	Tackling environmental tasks that can give innovation to new product/services model is always enjoyable.	0.921			
	GIM4	Improving existing green ideas during the design phase of new product/services model is always enjoyable.	0.870			
	GIM5	New green ideas to facilitate the community through new product/services model is exciting.	0.681			
	GIM6	Becoming further engaged in the development of green ideas through product/services model is desirable.	0.915			
	GIM7	Applying green ideas during the design phase of new product/services model is of personal interest.	0.872			
	GIM8	Coming up with new green ideas for our new product/services design is always enjoyable.	0.722			
GTRS	GTRS1	The project director/leader rewards the team with verbal appreciation for adding green environment features in the product/services model.	0.748	0.891	0.836	0.673
	GTRS2	The project director/leader rewards the team by monetary appreciation for adding green environment features in the product/services model design.	0.891			
	GTRS3	The team project director/leader punished the team by words of mouth for missing green environment features in the product/services model.	0.863			
	GTRS4	The project director/leader punished the team through fine for missing green environment features in the product/services model.	0.770			

Continued Table 2: Assessment result of measurement model

Construct		Indicator	Loading factor	Composite reliability	Cronbach alpha	AVE
GCT	GCR1	The team always come up with new ways to achieve environmental goals through innovative product/services model.	0.727	0.907	0.876	0.620
	GCR2	The team always propose new green ideas to improve environmental performance through innovative product/services model.	0.761			
	GCR3	The team always promote and champion new green ideas to others through innovation in their product/services model.	0.908			
	GCR4	The team always develop adequate plans for the implementation of new green ideas through innovative product/services model.	0.843			
	GCR5	The team always rethink new green ideas through innovative product/services model	0.708			
	GCR6	The team always try to find out creative solutions to environmental problems innovation in product/services model.	0.761			

Table 3: Discriminant validity

Variable	GCT	GIM	GTRF	GTRS
GCT	(0.788)			
GIM	0.375 (0.401)	(0.842)		
GTRF	0.606 (0.661)	0.498 (0.511)	(0.769)	
GTRS	0.456 (0.521)	0.519 (0.578)	0.541 (0.597)	(0.820)

values are higher than 0.50, indicating that the model is a good fit for further analysis (Hair *et al.,* 2017). In order to validate the discriminant validity between the latent variables, the Hetrotrait Monotrait (HTMT) correlation procedure and Fornell-Larcker results were presented with the square root of the AVE for each construct being higher than correlation between constructs. The findings presented in Table 3 shows that the square root of the AVE are higher than the correlation among the constructs. The Fornell-Larcker values are denoted in parentheses against each construct. On the other hand, the HTMT values are lower than 0.90 as recommended by Hair *et al.* (2021), indicating that measures are distinctive in nature.

Structural model assessment

In the second step, the internal model was analyzed through structural equation modeling to assess the relationship between exogenous and endogenous variables. In structural modeling, path coefficients are determined to validate the significance of relevancy of the structural model. The first step assessed collinearity through the variance inflation factor (VIF). In the current study, only one item which is GTRF10 which has a VIF value that is higher than 30 was subsequently removed, therefore ensuring that the basic assumption of the model is not violated. The direct relationships between variables are then investigated using the 500 bootstrap re-sampling procedure in SmartPLS. The empirical results detailed in Table 4 state that except for H2 (GTRS → GCT), all the hypotheses are supported as the bootstrap (t-values) are higher than (+/- 1.65). The highest significant relationship observed was for H5 (GTRF → GIM) (f^2=0.546) as well as H3 (GIM → GCT) creativity (f^2=0.128). Ghazali *et al.,* (2022) found that GTFL is a significant contributor in shaping employees' GCT in Pakistan's small and médium Enterprise sector. Similar results were corrobarated in earlier studies by Li *et al.,* (2020) for their study of electronic workers in China. Because the effect size (f^2) describes the value of change

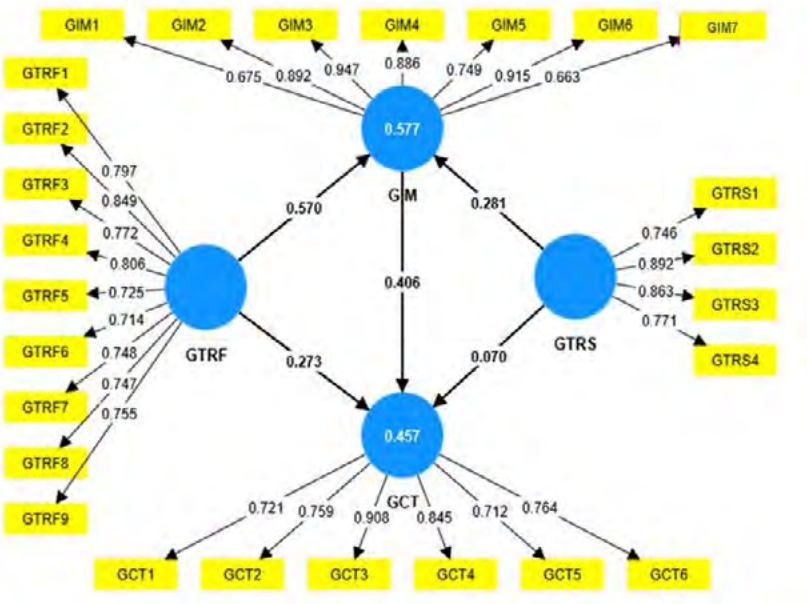

Fig. 1: Direct effect, structural model assessment and factor loading

Table 4: Structural model assessment (direct effect result and decision)

Hypotheses	Relationship	Original sample mean (O)	Sample mean (M)	SD	T statistics (|O/SD|)	P-values	f^2	CI [97.5%]	Decision
H1	GTRF → GCT	0.273	0.276	0.098	2.780	0.005	0.063	(0.085 and 0.476)	Accepted
H2	GTRS → GCT	0.070	0.069	0.105	0.660	0.509	0.006	(-0.132 and 0.289)	Rejected
H3	GIM → GCT	0.406	0.408	0.115	3.536	0.000	0.128	(0.174 and 0.625)	Accepted
H4	GTRS → GIM	0.281	0.28	0.082	3.425	0.001	0.132	(0.123 and 0.442)	Accepted
H5	GTRF → GIM	0.570	0.573	0.086	6.625	0.000	0.546	(0.392 and 0.724)	Accepted

in R^2 and from the findings it clearly explained that the f^2 value fulfills the assumption proposed by Cohen (1992). Contrary to our hypothesised relationship between green transactional leadership and green creativity, the results indicate an insignificant relationship. Table 5 shows the path coefficient relationship for the mediating variables and indirect effect. According to the findings, GIM mediates the relationship for both styles of leadership and students GCT, hence both H6 and H7 are accepted. Results from the study of Faraz *et al.,* (2021) confirm that GIM plays a contributory role in shaping pro-environmental behavior amongst employees. From the results obtained, the evidence suggests that a stronger impact can be observed for GTRF if compared to GTRS.

Table 6 presents the value of the R^2 to better understand how the independent variable is able to describe the dependent variable in the study. The contribution given by GTRF and GTRS on GCT was 45.7% while the contribution of GTRF, GTRS and GCT on GIM was 57.7%.

Direct effect

GTRF is the most important style of leadership practiced in higher education institutions to promote intrinsic motivation for clean and green environment

Table 5: Structural model assessment (indirect effect result and decision)

Hypotheses	Relationship	Original sample mean (O)	Sample mean (M)	STDEV	T statistics (|O/SD|)	P-values	CI [97.5%]	Decision
H6	GTRF → GIM → GCT	0.231	0.233	0.074	3.129	0.002	(0.095 and 0.383)	Accepted
H7	GTRS → GIM → GCT	0.114	0.115	0.049	2.322	0.020	(0.034 and 0.226)	Accepted

Table 6: R-square (R^2)

Construct	R-square	Adjusted R-square
GCT	0.457	0.439
GIM	0.577	0.566

among students who are working on their final year projects. The current study's findings align with previous studies conducted in different organizational settings (Li *et al.,* 2020). Students' perception and interest to protect the nature from pollution and health hazard issues through their innovative product and process modeling is a sign of maturity and their serious concern to safeguard the environment. Transformational leadership is that kind of leadership approch which infuses motivation among followers to think deeply for a viable solution to problems. Hence, in academia it is actually the perception and motivation of supervisors to promote clean and green environmental agenda through teaching practices and innovative models to their students. In case faculty members (irrespective of their specialty) have the vision of promoting a sustainable environment, then they can motivate and engage their students for better planning to safeguard nature from future hazards. The results presented in Table 4 also depict that GTFL promotes a culture of innovation that results in the green creativity approach which provides solutions to the existing industrial development models. Previous studies also found similar results for their study conducted in the industrial sector in China. GCT is the approach to solving problems arising from water, plastic, visual pollution, soil radioactive contamination, and thermal pollution. Across the world, higher education institutions are supported through research grants for solutions to issues affecting the natural environment. Large manufacturing firms also focuses on reducing their impact in polluting the environment through investment in green research and development. Because of these efforts, sustainable production techniques are now being introduced in various spheres of life. As it is the common theme that today's students became future leaders, hence nurturing students with the caring intention for a sustainable future will play a pivotal role in promoting the cause for a greener environment for future generations. Hence, the university faculty members can mould and transform the students' intention through group goal behaviors to introduce new practices via product development and process reengineering for active participation in safeguarding the environment. The current study introduces GTRS behavior to understand the dynamic relationship between students' GIM and their creativity. In this regard, the results indicate that up to a certain extent, green intrinsic motivation is related to GTRS, however green creativity does not have any kind of relationship with GTRS. Results from previous studies (Mittal and Dhar, 2016) state that intrinsic motivation is one's feeling associated with inner satisfaction through belief, perception and recognition. Based on the findings from Faraz *et al*., (2021), transactional leadership boosts one's intrinsic motivation through reward and punishment to perform better and practice innovative behaviors at the workplace. Hence, it can be observed from the results of the current study that reward and punishment concept (by faculty members) in the form of marks allocation on completion of final year project enhances students' GIM to work on sustainable environmental approaches. In contrast, GTRS did not indicate any kind of relationship with students' GCT. The results are in contrast to the findings of Ma and Jiang, (2018) which

posit that transactional leadership promotes creativity in comparison to transformational leadership. Results from our study depict that GIM enhances the GCT level of students. Based on the theoretical underpinning of the self-determination approach (Deci and Ryan, 2012; Ryan and Deci, 2017) and the results of Kanat-Maymon *et al.,* (2020), it is evident that individuals design policies (intrinsic motivation) for their selves based on the perception of the outcomes and then act accordingly. The current study interestingly highlighted that GTRS acts as a catalyst in moulding the GIM of students to focus on green and eco-friendly solutions for their final year project problems.

Indirect effect (Mediating effect)

The current study also validates the mediating role of students GIM between the supervisors' (faculty members) GTRF and GCT in H6. The findings indicate that the supervisors' knowledge towards green and eco-friendly environment and their interest in promoting a culture of sustainability motivates students to work towards developing environmentally-safe solutions to the existing problem, which ultimately boosts their creativity through green product and process redesign approach of the students. Similar findings were observed in the study of Li *et al*., (2020) in China. Their results focussed on designing a strategy by green transformational leaders at the organizational level that promotes employees green intrinsic motivation and the culture of innovation and creativity in the manufacturing sector. Furthermore, the current study moves one step forward and investigates the mediating role of GTRS between students' GIM and their creativity for green product/process development. The results indicate that the students' green product/process motivation partially mediates the relationship between GTRS and GCT level. These findings are informative in nature as GTRS is investigated for the first time from the context of environmental and green behavioral research. Until the emergence of the GTRF concept by Chen and Chang, (2013), no study had investigated the role of GTRS to understand the nature of different styles of leadership as proposed by Bass and Avolio, (1993). In short, GTRF is mostly investigated in the manufacturing sector, SMEs and hospitality industry by different researchers and the evidence from academia had not received the adequate attention that it deserves (Cao and Chen, 2019; Gonzalez *et al.*, 2022; Fawehinmi *et al.*, 2020; Fernando *et al*., 2020). Hence, the current study opens new vistas of opportunity for researchers to investigate GTRF of supervisors/faculty members as well as students' GIM for green product development in greater depth. In the future, these university students can perform their duty in various organizational setups and promote the culture of green and eco-friendly approaches to achieve sustainable development goals.

CONCLUSION

In higher education institutions, faculty members' awareness about hazards to the natural environment must be shared with students, preparing them for future challenges and inculcating their active role for green products and process creativity. The findings indicate that GTRF has significant contribution in shaping students' GCT through GIM, which is a novel finding of this study that sheds light on the importance of the teaching faculty members' role as a catalyst in promoting green behaviors among students during their studies. In this regard, the personality of faculty members and their role of leadership while supervising students in projects play a crucial role in developing and motivating students for eco-friendly solutions to existing product/services through green creativity approach. Based on the findings of the current study that GTRF plays an important role in shaping students' GIM and GCT, it is recommended that future researchers examine this relationship at different institutional setups i.e. schools, colleges and public and private universities, which will inevitably enrich the corpus of knowledge on green approaches for students. Recent studies have indicated various managerial implications for stakeholders related to higher education authorities, behavioral scientists and environmental researchers. First of all, higher education commissions/departments should encourage students to work on green product development and process design through their educational activities. It is mandatory to foster the culture of green leadership in higher education institutions through training and development programs. The Pakistan Higher Education Commission should conduct trainings on green product development and process innovation by leading trainers at the regional and provincial levels. These experienced trainers may initiate these green concepts to nurture and grow green leadership and GCT amongst faculty and students. Students' creativity for green product can be increased through joint work of academia and industrial hubs. In this regard, groups of students under the supervision of faculty members (that has serious mindfulness attitude for sustainability of environment)

must work for industrial setup and in case of providing solutions, the team may be rewarded in the form of patent registration with specific proportion of equity for that group. Once such an environment is nurtured, students' intrinsic motivation for eco-friendly production will be increased, therefore fostering a culture of new eco-friendly startups and creating green entrepreneurship that may ready to play their role in achieving sustainable development goals. It would be possible to promote the culture of GTRF and GTRS in higher education through governmental policy and initiatives. The current research has several limitations, so suggestions for future researchers are put forth. The current study is focused on selected universities in the Khyber Paktoonkhwa region of Pakistan, hence its results cannot be generalized to other regions and locations. Future researchers may investigate the current model in their own higher education setup and then compare the results with the current study. Secondly, the current study investigates only GIM as a possible mediator, however future researchers may validate the model by comparing the meditational part of both intrinsic and extrinsic motivation to understand students' intentions better while working towards GCT. Thirdly, future studies may also investigate the moderating role of green mindfulness, students' demographic attributes and their efficacy beliefs in HEIs to understand the dynamic relationship between leaders and followers in promoting green and eco-friendly environment for future generations.

AUTHOR CONTRIBUTIONS

N. Saif conducted the conception and design, acquisition, analysis and interpretation of data, drafting and critical revision of the manuscript and statistical analysis. G.G.G. Goh conducted the conception and design, drafting and critical revision of the manuscript, support and supervision of the study. J.W. Ong conducted the drafting and critical revision of the manuscript, support and supervision of the study. I.U. Khan performed the analysis and interpretation of data and statistical analysis

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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
AVE	Average variance extracted
CI	Confidence interval
CR	Composite reliability
et al.	Et alia
f2	Effect size
Fig.	Figure
GCT	Green creativity
GIM	Green intrinsic motivation
GTRF	Green transactional leadership
GTRS	Green transformational leadership
HTMT	Hetrotrait monotrait
H1	Hypothesis 1
H2	Hypothesis 2

H3	Hypothesis 3
H4	Hypothesis 4
H5	Hypothesis 5
H6	Hypothesis 6
H7	Hypothesis 7
O	Original sample mean
PLS	Partial least square
p-value	Probability value
R2	Determination coefficient
SD	Standard deviation
SMART PLS	Measurement model assessment
STDEV	Standard deviation of the estimated parameter over all subsamples
t-test	Hypothesis test statistic
VIF	Variance inflation factor

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CASE STUDY

Urban green space during the Coronavirus disease pandemic with regard to the socioeconomic characteristics

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ABSTRACT

BACKGROUND AND OBJECTIVES: The spread of Coronavirus disease limited the activities of humans in the globe in 2020 with Jakarta reported to have also struggled with the virus. The pandemic stopped humans from visiting public amenities such as urban green spaces which are one of the key components of sustainable and livable cities and have the ability to reduce the negative impact on mental health. However, there are limited studies on the behaviors and perceptions of humans toward the usage of urban green spaces during the pandemic. Therefore, this study was conducted to determine the changes in the behaviors, perceptions, and visitation of residents towards the urban green space during the pandemic based on the socioeconomic aspects as well as the access and proximity to the parks and urban forests.

METHODS: A questionnaire was distributed through an online survey on social media for approximately two months, from March to April 2021, and the last data recorded showed there were 1,660 respondents. The attention was on their perceptions and visitation to the urban green spaces spread across administrative cities in Jakarta, representing 42 districts and 239 sub-districts. Data obtained were analyzed empirically using the partial least square structural equation approach and SmartPLS 3.0 software to determine the relationship between the respondents' characteristics and proximity to urban green space visitation.

FINDINGS: The results showed that almost half of the respondents perceived changes in the urban green spaces and the majority believed the spaces were more useful during the pandemic. It was also discovered that the socioeconomic characteristics of the respondents including age, education level, occupational status, and average monthly income differed statistically significantly from the criteria associated with the visitation to urban green spaces during the pandemic. The findings indicated that education was substantially associated with the decision to exercise and engage in outdoor recreation in urban green spaces. Meanwhile, not all houses close to the parks and urban forests have a statistically significant impact on their usage and this is the explanation for the non-correlation and non-causation.

CONCLUSION: This study showed that the perception of urban green space by the people changed during the pandemic but its usage was reduced due to the closures and restriction policies implemented. It was also discovered that socioeconomic characteristics have a significant influence on visitation but not all accessibility factors were significantly affected and this is different from the findings of previous studies. Moreover, this study discussed and shared empirical evidence that depicts urban green space as a resilient urban infrastructure during the pandemic. This means it is necessary to promote sustainable urban planning through the development of urban green spaces to manage the medium and long-term crises.

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INTRODUCTION

Corona Virus Disease 2019 (COVID-19) first appeared in Wuhan, China, and was later declared an outbreak an international public health emergency on January 30, 2020 by the World Health Organization (WHO). The primary step implemented to suppress the spread was to reduce social contact in the community. Several countries also set quarantine policies and social restrictions to prevent infection and ensured health supervision. The pandemic affected all the countries in the globe, including Indonesia. It was discovered from the government data published that there were 6,708,737 cases, with 160,384 deaths in the country as of December 17, 2022 and this was the highest in Southeast Asia. As the capital city of Indonesia, Jakarta has the highest number of cases with 1,425,915 which is 22,2 Percent (%) of the total recorded in the country. This led the Jakarta Capital City Government (JCCG) to issue a Large-Scale Social Restriction policy to limit the spread, of the virus and this involved the restrictions placed on urban green spaces (UGS). It was also noted that exercise and recreational activities were limited and reduced (Giustino *et al*., 2020). However, it was reported in a previous study that the closure of UGS is not the right solution for communities (Lopez *et al*., 2020). This was associated with the ability of these spaces to positively influence mental health, specifically during a pandemic (Brooks *et al*., 2020) considering the possibility of the social restrictions causing depression in humans (Fitzpatrick *et al*., 2020). The advantages of the UGS include its ability to deliver ecological services, enhance the quality of life, improve the community's physical and mental health, and ensure urban sustainability. Fascinating investigations have been conducted on the link between UGS and human well-being and it was reported that the relationship between these concepts is vital for urban planning (Haq, 2011). This is due to the ability of the UGS to provide environmental services, ecology, social facilities, psychological benefits for society and human life (Chiesura, 2004), ecosystem services to urban residents (Larondelle *et al.,* 2014), ecological and economic value (Wu *et al*., 2015), social benefits, contribution to public health (Wolch *et al*., 2014) and an improvement in the quality of urban life and public welfare (Villanueva *et al*., 2015). It was also believed to be an essential component of complex ecosystems (Brown *et al*., 2014). Moreover, a previous study indicated the need to investigate the relationship between green infrastructure, ecosystems, and public health in the context of sustainable development (Khoshnava *et al.,* 2020). It has been recommended that urban planners should consider the management of UGS in meeting the needs and expectations of communities and this indicates its importance in regional development. Law Number 26 of 2007 concerning Spatial Planning requires UGS to cover at least 30% of the urban area in Indonesia. This was observed to have led the JCCG to project the development of 30% UGS in 2030 as stated in the Jakarta Spatial Planning 2030. The latest regulation on planning is the Governor Regulation Number 31 of 2022 concerning Detailed Spatial Plans for Planning Areas in Jakarta Province and was observed to have reduced the percentage of built-up area for the UGS zone to 4,804.89 ha or 7.56% from the figure stated in the previous regulation. Jakarta is Indonesia's most populated city and this means there were unique hurdles to preventing the spread of the virus. This was supported by previous findings that a high population density multiplies the effects of pandemic spread (Stier *et al*., 2020; Sobral *et al*., 2020). Therefore, UGS was considered an important factor in determining the quality of urbanization (Carpentieri *et al*., 2020). This is important because the pandemic affected air pollution in urban areas (Masum and Pal, 2020) as well as air quality parameters (Abu-Qdais *et al.,* 2020). It was also noted by Naderipour *et al.* (2020) that the social restriction policies implemented during the period reduced carbon footprint, carbon dioxide (CO_2) emissions, and improved energy savings. The pandemic threatened human mental and physical health with severe psychological consequences for humans (Bavel *et al*. 2020). This is in addition to the fact that the rapid economic growth and urbanization in developing countries have increased public environmental awareness (Oryani *et al*., 2022). The phenomenon has spurred previous studies to better understand the different planning priorities between the equity of social justice, economy, and environmental protection using the triangular model (Campbell, 2016). It has been discovered that urban development often comes at the expense of green areas and this has created challenges for planners and policymakers to protect open spaces (Bengston *et al*., 2004). A previous study showed that the efforts and policy initiatives of the JCCG to improve public parks, protect urban forests, and develop public green spaces are insufficient due to

an increase in the city population (Hwang *et al*. 2020). For example, the land use changes in the Jabodetabek area are dominated by an annual increase in the conversion to concentrated urban activities (Rustiadi *et al*., 2015). A geographic information system study also showed that the UGS in Jakarta decreased by 342.40 hectares (ha) from 2011 to 2018 with the highest recorded in the green belt zone (Setiowati *et al*., 2019). The UGS area in the city has also been ranked lowest compared to other big cities in the country and the globe (Setiowati *et al*., 2018). Furthermore, the data from Jakarta Satu showed that the highest and lowest distribution of UGS were 31.15% and 8.8% in East and West Jakarta, respectively. Kabisch and Haase (2014) reported that recreation in UGS has the ability to improve the quality of life. It was discovered by De Kleyn *et al.* (2020) that the activity mostly conducted in these spaces by communities during the pandemic was exercise. Therefore, the high conversion of UGS into built-up land in Jakarta possibly influenced the perceptions of the residents, specifically during the pandemic when there is an increase in the need for its usage. It is important to note that UGS planning and implementation are usually based on the incorporation of the values and lifestyles of the community. This means there is a need for more studies on the application and preference of UGS in rapidly urbanizing cities of developing countries (Wendel *et al*., 2011; Willemse, 2010). This also shows it is important to analyze perceptions of urban residents in order to improve the planning and management of UGS in times of crisis. Several studies have been conducted on the function of UGS but there was no focus on its usefulness during the pandemic. Therefore, this study was conducted based on the previous studies conducted in relation to the changes in behavior and attitudes towards the visitation to UGS during the COVID-19 pandemic as observed in Lopez *et al.* (2020) in New York, United States, and Ugolini *et al.* (2020) in six European countries using different analytical methods. A combination of non-physical (socio-economics) and physical factors (accessibility to UGS) was considered in this present study using a partial least-squares structural equation modeling (PLS-SEM) techniques to determine the impact of community visits to UGS during pandemics in densely populated cities of developing countries. The findings are expected to serve as recommendations for the government to manage UGS in the "new normal" period and review policies set during the pandemic. They are also to provide an insight to urban planners and stakeholders that UGS is part of the green infrastructure resilience required in future crises. It is important to note that this is the first study to investigate the relationship between respondents' socioeconomic characteristics and proximity to UGS visits during a pandemic in Indonesia. The aims of the study are to 1) investigate the perception and behavior of residents' towards UGS during the pandemic, 2) analyze UGS visitations based on the socioeconomic characteristics of the residents during the pandemic, and 3) analyze UGS visitations during the pandemic based on residential proximity to UGS. This study was conducted in Jakarta, the capital of Indonesia, during the 2021 pandemic.

MATERIALS AND METHODS

Study area

Jakarta is the capital city of Indonesia with a land area of 662.33-kilometer square (km^2) and an ocean area of 6,977.5 km^2 as indicated in Fig. 1. The Province is divided into 5 administrative cities, 1 administrative district, and 44 sub-districts, 267 sub-districts, 2,731 residential units, and 30,417 neighborhood units. There are also 261 urban villages in South, North, East, West, and Central Jakarta. The 2021 Population Census conducted showed that there 10,562,088 people in the province with an annual population growth rate of 0.92 and a density is 14,555 people/square kilometer (people/km^2). This means it is the densest city in the country. Moreover, Jakarta is bordered to the north of the coast by approximately 35 kilometers (km) with nine rivers and two canals flow surrounding the Java Sea, to the south and east by West Java Province, and to the west by Banten Province. The city is located in the lowlands with an average elevation of 7 meters (m) above sea level and approximately 40% of its area is plains with a land surface 1−1.5 m below sea level. The hydrological conditions of Jakarta are represented by sub-watersheds (Central Bureau of Statistics, 2022). It also has two watersheds which include the Cisadane and Ciliwung River basins. The Ciliwung River has an estuary at Mount Pangrango, flows through Bogor, Depok, to Jakarta, and is considered the longest river in the city with a length of 46,200 m. It is pertinent to state that Jakarta has 13 rivers, 2 canals, and 2 floodways including the West and East Flood Canals designed to deal with flooding.

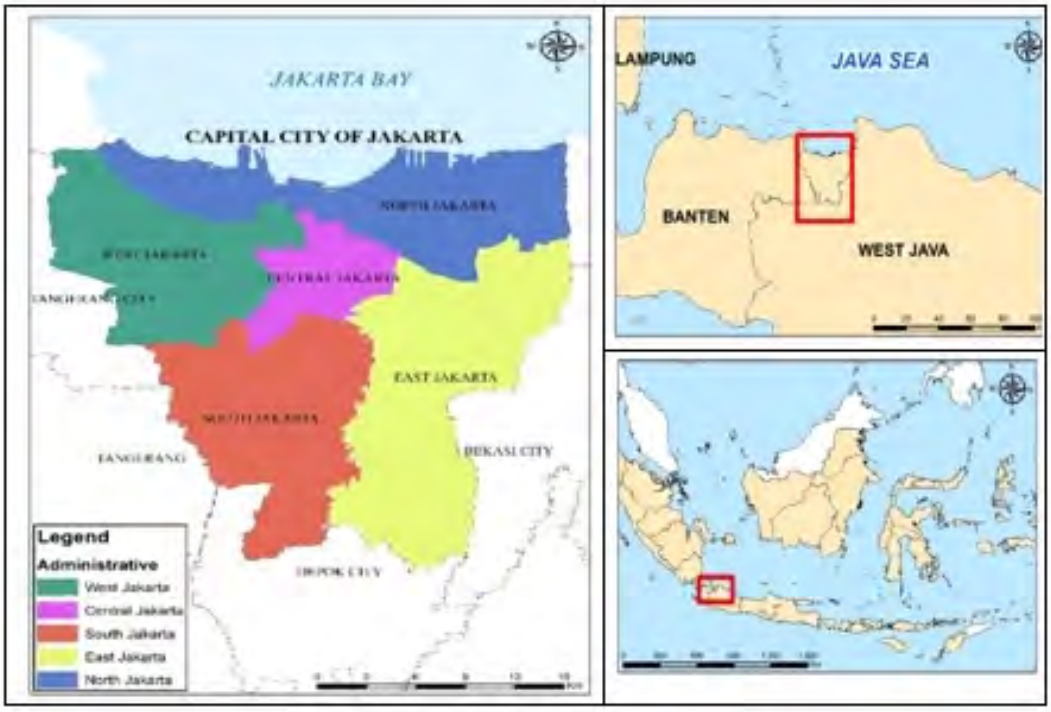

Fig. 1: Geographic location of the study area in Jakarta Capital City, Indonesia (Setiowati *et al.,* 2018)

Analysis of data

Data collection

Data were collected through a questionnaire circulated through an online survey on social media for approximately two months, from March to April 2021, and the data last recorded showed that there were 1,660 respondents representing 239 urban villages. It was discovered from the final results that there were 22 sub-districts without respondents including 6 in South Jakarta, 6 in East Jakarta, 4 in Central Jakarta, and 6 in West Jakarta. The questionnaire contained information on the characteristics of the respondents including the residential location, education level, occupational status, average monthly income, and age were obtained. Some key questions were also asked such as the perception of the respondents concerning UGS, proximity to UGS (park and urban forest) from their residential location, and visitation frequency for outdoor recreation and exercise activities during the COVID-19 pandemic.

Data analysis

This study analyzed the changes in the perceptions of people concerning UGS during the COVID-19 pandemic. It was based on the report of previous studies that the residents perceived the UGS to be more useful during the period because the facilities were resilient. The public perceptions were analyzed using descriptive analysis of the data obtained through a questionnaire. The PLS-SEM technique was applied to predict the perception and use of UGS during the pandemic and the conceptual framework model was observed to be complex as indicated in Fig. 3. It is important to note that SEM is a technique normally used to evaluate complex theoretical relationships between several variables, specifically when conducting social science study (Hair and Alamer, 2022). The two fundamental SEM methods are covariance-based structural equation modeling and PLS-SEM which are discovered to have been applied more frequently in recent times due to the shift in the attention of researchers to these methods (Ringle *et al.,* 2015). It has been previously reported that PLS-SEM supports external validity when the data assumption is non-normal and requires a better understanding of the theoretical model (Hair and Alamer, 2022). It normally uses the mean, median,

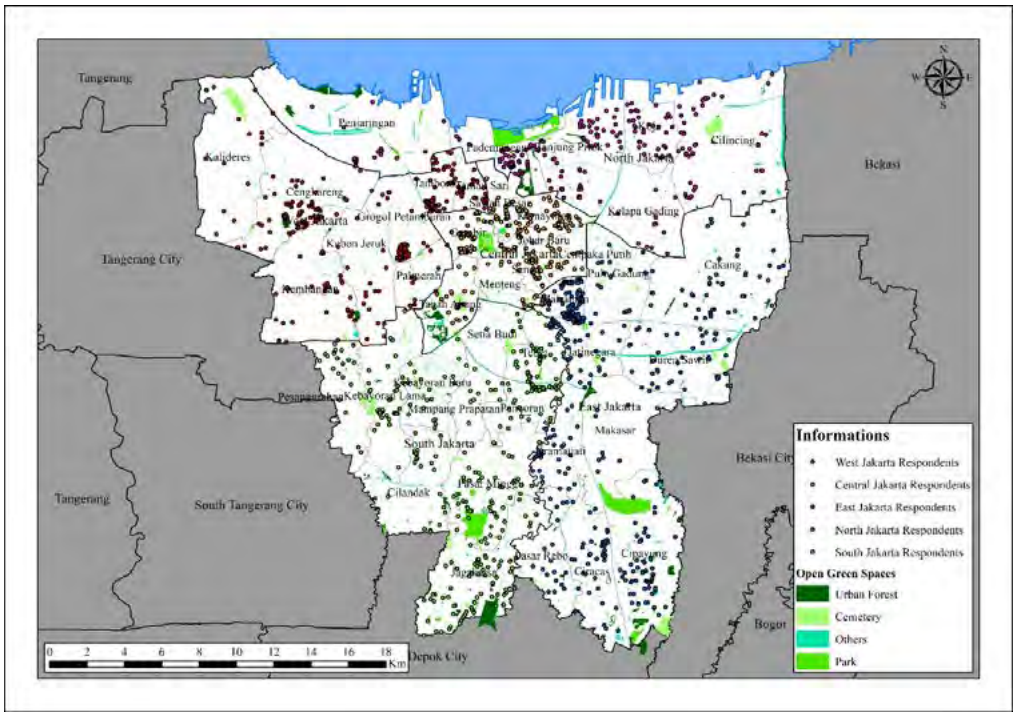

Fig. 2: Distribution of respondents and UGS in Jakarta Province, Indonesia

and standard deviation (SD) to compare two or more data sets to determine the difference in data (Yen *et al.,* 2017). Methodologically, PLS-SEM is a structured path estimation and essential multivariate analysis method to estimate the relationship between latent variables in SEM and is usually completed using Smart Partial Least Square (SmartPLS) software (Ringle *et al.,* 2015). The software was used to determine the relationship between respondent characteristics and UGS visits based on the data from the questionnaire. Meanwhile, the PLS-SEM determined the significance of the characteristics of respondents and the proximity of the UGS to their houses. The path coefficients of the structural model were determined using PLS algorithms based on the criteria that the significant path at P (Probability) ≤ 0.05 at a 95% confidence level and P ≤ 0.01 at a 99% confidence level. This means the three main steps applied in this study include a literature review, an open-ended questionnaire, and data analysis.

RESULTS AND DISCUSSION

Respondents' characteristics

A total of 1,660 responses were obtained from 44 sub-districts and 239 urban villages in Jakarta as presented in Fig. 2. It was discovered that 94.1% of respondents were in the productive age of 20−60 years old, 3.67% were elderly, and 2.23% were less than 20 years old. The findings also showed that 60.54% obtained a high school degree and 38.86% had a university-level one certificate. The percentage is high compared to other provinces in Indonesia because Jakarta has the highest level of education enrollment. Moreover, most respondents were unemployed and made an income below the Jakarta Provincial Minimum Wage of 297.20 United States Dollars (USD) in 2022 followed by those with 297.20 – 660.42 USD. It was also discovered that they have different occupational statuses with 422 (25.42%) found to be working in the government/ private sectors, 24.82% were unemployed, and 5.72% were blue-collar laborers while the others, 34.16%, had other occupations outside the previously mentioned categories. The summary of these socioeconomic characteristics is presented in the following Table 1.

The correlation between the respondents' residence proximity to UGS facilities such as parks and urban forests and visitation during the pandemic was also analyzed. The findings showed that the percentage

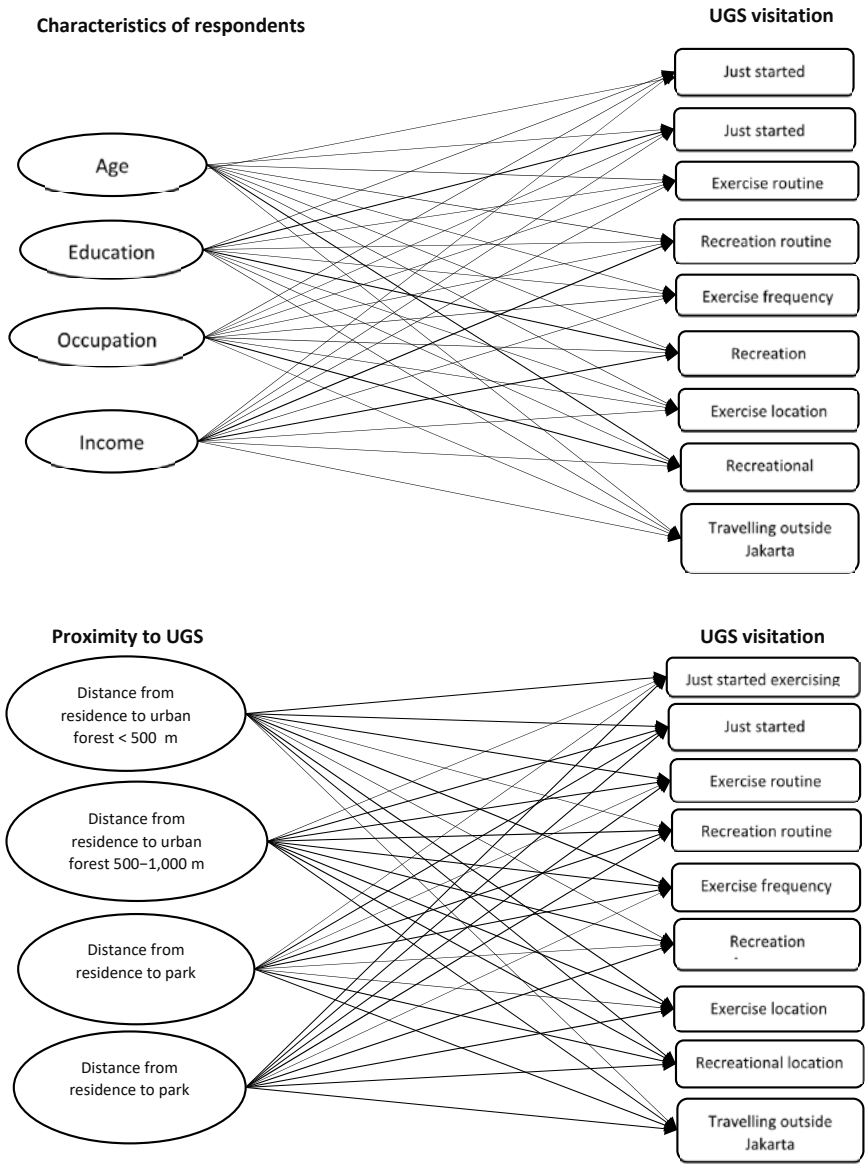

Fig. 3: The conceptual framework

of visitation by those living less than 500 was only 11.27% while those within 500–1,000 had 21.08%. It was also discovered that visitation to parks was higher than to urban forests. This was indicated by the fact that the percentage of visitation to the park during the pandemic was 25.12% and 33.55%, respectively, for the two locations. Moreover, the percentage of people engaged in exercises and recreation routines reduced during the pandemic by 74.4% and 79.58%, respectively as previously explained by Setiowati *et al.* (2022). This empirically means some people still engaged in recreational and exercise activities at the time despite the restriction policies made by the government to close the parks and forests. A total of 26.63% and 21.08% were discovered to have just started visiting UGS during the pandemic for exercise and recreation activities respectively. This is in line with the findings of Setiowati *et al.* (2022) that

10.4% and 11.27% were motivated to visit parks for recreational and exercise activities respectively due to health reasons and to reduce stress and boredom caused by negative deviations from conditions before and during the pandemic. The data analysis also showed that 10.60% of respondents less than 20 years and within the productive age of 20-60 years visited urban forests located < 500 m while only 0.42% of the elderly respondents > 60 years visited. Meanwhile, the figures for the proximity within 500−1,000 m for < 20 years, 20-60 years, and > 60 years was recorded to be 18.67%, 19.76%, and 0.84%, respectively. It was also discovered that there were more visits to the parks within a radius of < 500 m compared to urban forests for respondents < 20 years, 20-60 years, and > 60 years with 23.49%, 23.19%, and 1.08%, respectively. The values for the 500−1,000 m distance were recorded to be 30.24%, 32.05%, and 0.96%, respectively, and these are believed to be higher than the other accessible options. It is important to note that those < 20 years and 20−60 years had similar visit trends to UGS during the pandemic. Furthermore, the results showed that 24.70% of 20−60-year-old respondents started exercising, 19.94% engaged in outdoor recreation, and 25.66% traveled outside Jakarta solely to conduct activities at UGS during the pandemic. This confirmed the opinion of a previous study that UGS was used for recreational and exercise activities in Jakarta during the pandemic (Ugolini *et al.*, 2020). The study further showed that the motivation of the respondents studied was reduced to the decrease in the UGS visits despite the importance of these spaces in providing a place for relaxation, rest, and exercise. This is in line with the findings of this study that some respondents perceived the presence of UGS as necessary during the pandemic as indicated by 19.64% and 17.05% that did not change their exercise and recreation habits respectively. The summary of these findings is presented in Table 2 while the conceptual framework designed to assess the patterns of direct correlations between the characteristics of the respondents and their motivations to visit UGS as well as between residential proximity and motivations for visitation is indicated in Fig. 3.

Respondents' perception of UGS

The differences in individual values concerning infrastructure and institutions have been discovered to be based on relationship dimensions, knowledge, demographics, socioeconomic status, value orientation, learning interviews, and questionnaires (Allen and Cochrane, 2010; Silver *et al.*, 2010). The equitable and inclusive distribution of UGS to achieve sustainability in Jakarta is a challenge for JCCG and this is the reason it is important to discuss the changes in the perception of the residents. Indonesia struggled with the COVID-19 pandemic and has the highest cases in Southeast Asia while Jakarta was found to be the province with the highest in the country. This motivated the JCCG and National Government to issue a policy for social restriction, including closing parks and urban forests, in 2020. These news policies and changes in plans were required during the period due to the emergence of new behaviors and needs caused by the pandemic (Honey-Rosés *et al.*, 2020). The findings from the survey conducted showed that

Table 1: Socioeconomic characteristics of respondents

Variable	Sub-variable	Frequency	Percentage
Age	< 20 Years old	37	2.23
	20−60 Years old	1,562	94.1
	> 60 Years old	61	3.67
Education level	Non-educated/non-degree	10	0.6
	Graduated from high schools	1,005	60.54
	College graduates	645	38.86
Occupational status	Unemployed	412	24.82
	Government/private sectors	422	25.42
	Entrepreneur	164	9.88
	Blue-collar laborer	95	5.72
	Others	567	34.16
Average monthly income	IDR < 297.20 USD	1,134	68.31
	IDR 297.20 – 660.42 USD	264	15.9
	IDR 660.43 – 1,320.87 USD	89	5.36
	IDR > 1,320.87 USD	173	10.42

the people perceived a change in UGS during the pandemic. Most of them said that the space provided more assistance. This means UGS is beneficial for both the mental and physical health (Ugolini *et al*., 2020) caused by the social restrictions and quarantine normally imposed in times of crisis. The results are believed to be a response to the recommendations made by Willemse (2010) and Wendel *et al*. (2011) to study the usage and preferences of UGS in cities experiencing rapid urbanization in developing countries such as Jakarta. Geng *et al*. (2021) also reported that green spaces served as a source of resilience during the pandemic partly due to their positive effects on the psychological, physical, and social cohesion of humans. Meanwhile, Wendel *et al*. (2011) stated that the lack of assessment regarding the distribution and accessibility factors has reduced the lands allocated for UGS. It was also discovered that the urbanization in Jakarta is suppressing the quantity of UGS and this led to the discussion on the preferences of the residents in line with the quality of the activities being conducted in these spaces (Van Oijstaeijen *et al*., 2020). Another study also showed that there is a change in the behavior of communities towards UGS during the pandemic with some people reported to be visiting these spaces for exercise and relaxation despite the social restrictions imposed (Ugolini *et al*., 2020). The findings of this study showed that the highest change in the perception of the people at the time was recorded in Central Jakarta at 47.55% while the lowest

Table 2: Proximity to UGS and motivation for visitation

Questions	Answers	Frequency	Percentage
The distance of the residence from the urban forest < 500 m	No	1,473	88.73
	Yes	187	11.27
The distance of the residence from the urban forest 500−1,000 m	No	1,310	78.92
	Yes	350	21.08
The distance of the residence from the park < 500 m	No	1,243	74.88
	Yes	417	25.12
The distance of the residence from the park 500−1,000 m	No	1,103	66.45
	Yes	557	33.55
During the COVID-19 pandemic, did you just start exercising at UGS?	No	1,218	73.37
	Yes	442	26.63
During the COVID-19 pandemic, did you just start recreation at UGS?	No	1,310	78.92
	Yes	350	21.08
During the COVID-19 pandemic, how was your exercise routine at UGS?	Decreased	1,235	74.4
	Same as Before/No Change	326	19.64
	Increased	99	5.96
During the COVID-19 pandemic, how was your recreation routine at UGS?	Decreased	1,321	79.58
	Same as Before/No Change	283	17.05
	Increased	56	3.37
During the COVID-19 pandemic, how often did you exercise at UGS?	Once a week	196	11.81
	Once a month	399	24.04
	Not a routine	67	4.04
	Never	998	60.12
During the COVID-19 pandemic, how often did you have recreation at UGS?	Once a week	109	10.4
	Once a month	257	24.52
	Not a routine	99	9.45
	Never	583	55.63
During the COVID-19 pandemic, where was the UGS location you go for exercise?	Jakarta	977	58.86
	Outside Jakarta	35	2.11
	Jakarta and Outside Jakarta	126	7.59
	Never	522	31.45
During the COVID-19 pandemic, where was the UGS location you go for recreation?	Jakarta	781	47.05
	Outside Jakarta	63	3.8
	Jakarta and Outside Jakarta	181	10.9
	Never	635	38.25
During the COVID-19 pandemic, have you ever traveled outside Jakarta solely to carry out activities at UGS?	No	1,211	72.95
	Yes	449	27.05

was in South Jakarta at 44.71%. Moreover, a positive shift was recorded in the disposition of the people to these spaces as observed from the agreement of 73.24%–76.22% that the UGS was more beneficial during the pandemic with the highest found in Central Jakarta and the lowest in South Jakarta as presented in the following Table 3.

Visitation to urban green space

An interesting finding was that the respondents had started recreational and exercise activities because they considered UGS more useful during the pandemic and this indicates the ability of the green spaces to maintain physical and mental health. The awareness of these benefits influenced the behavioral intentions of the residents toward the usage of the UGS (Yen *et al.,* 2017). This is in line with the findings of another study that cultural differences influence user expectations and demands for UGS (Jim and Shan, 2013). Furthermore, access to the environmental benefits of UGS has emerged as an important concept in environmental justice. Previous studies identified accessibility as one of the main factors influencing the usage of UGS. For example, Byrne *et al.* (2009) showed that ease of access was an important reason for UGS visits and Wang *et al.* (2015a) identified it as a main factor influencing park utilization. Meanwhile, Douglas *et al*. (2020) reported that the initial response to worldwide restrictions was an increase in the usage of UGS for exercise and outdoor recreation. This shows that the people created a diversion and protected themselves from stress during the pandemic by visiting the UGS to experience urban nature. It was also discovered that the pandemic spurred the need to allot more green spaces in urban areas in the future as reported by Kleinschroth and Kowarik (2020) and Venter *et al.* (2020). The respondents' perceptions of UGS visitation during the pandemic were evaluated and the findings are presented in the following Table 4. It was discovered that 27% traveled outside Jakarta to visit UGS despite the restrictions on people's mobility. Moreover, the highest percentage of those willing to travel during the period was found to be 29.91% in East Jakarta while the lowest was 21.78% in West Jakarta. It is important to note that community preferences are likely to be influenced by the distribution, quality, and accessibility of UGS. This is the reason the behavioral transformation of the people during the COVID-19 pandemic promoted them to visit UGS, thereby leading to an increase in demand. There is a need for further studies related to the usage of UGS, specifically due to the changes observed during the COVID-19 pandemic, in order to enrich the findings of this study.

Table 4 shows that exercise-related activities were conducted more than recreational activities during the pandemic. It was also observed that most recreational activities were in East Jakarta and North Jakarta while the lowest were in South Jakarta. Moreover, some respondents indicated the willingness to travel outside the city for the sole purpose of engaging in UGS activities despite the social restrictions. This was observed to be in line with the findings of Venter *et al*. (2020) that the increasing positive relationship between UGS and the remoteness of its location indirectly reduced the spread of COVID-19. It was discovered that the location of residences close to the parks and urban forests influenced the willingness to visit these green spaces to exercise or engaged in recreation. A previous study also showed that several urban residents do not have the opportunity to live close to open spaces, even though it is essential for their health (de Kleyn *et al*., 2020). Dempsey and Dobson (2021) further indicated that the increase in the number of people exercising at the time showed the importance of the presence of UGS. Moreover, Slater *et al*. (2020) provided short and long-term recommendations to encourage access to the UGS limited by physical distance. Another study by Lopez *et al.* (2020) explained that the usage of UGS was considered more important for mental and physical health. The other factors associated with the usage

Table 3: Respondents' perceptions of UGS during the COVID-19 pandemic

No.	Administrative City	Transformation in the perception of UGS (%)		UGS is more useful (%)	
		'No'	'Yes'	'No'	'Yes'
1.	East Jakarta	52,90	47,10	25,22	74,78
2.	South Jakarta	55,29	44,71	26,76	73,24
3.	Center Jakarta	52,45	47,55	23,78	76,22
4.	West Jakarta	54,29	45,71	24,54	75,46
5.	North Jakarta	54,62	45,38	25,77	74,23

Table 4: Respondents' perceptions of UGS visitation during the COVID-19 pandemic in Jakarta

No.	Administrative City	Start recreation activities at UGS (%)		Start exercising at UGS (%)		Willingness to travel outside Jakarta to visit UGS (%)	
		No	Yes	No	Yes	No	Yes
1	East Jakarta	77,23	22,77	72,54	27,46	70,09	29,91
2	South Jakarta	82,06	17,94	75,29	24,71	70,29	29,71
3	Center Jakarta	77,62	22,38	73,08	26,92	73,78	26,22
4	West Jakarta	78,83	21,17	74,23	25,77	78,22	21,78
5	North Jakarta	79,23	20,77	71,54	28,46	73,85	26,15

of these spaces include the availability of leisure time (Lee, 2016) and income (Jim and Shan, 2013). However, the focus of this present study is on the relationship between socioeconomic characteristics variables and UGS visits with emphasis on 8 sub-variables including age, educational level, occupational status, average monthly income, less than 500 m and 500–1,000 m distance from the residential area to an urban forest or a park. Meanwhile, there were 9 sub-variables for the UGS visits and these include just started exercising at UGS during the COVID-19 pandemic, just started recreation activities during the COVID-19 pandemic, exercise routine, recreation activities routine, exercise frequency, recreation frequency, exercise location, recreational location, and willingness to travel outside Jakarta solely to conductive activities in UGS. It is important to note that urban planners are required to evaluate UGS by analyzing visitor profiles and preferences (Kabisch and Haase, 2014). There is also the need for the public sector to observe the dynamics and survey community needs (Panjaitan *et al.*, 2022). This is necessary because the flow of ecosystem services benefits is normally influenced by interactions between green infrastructure, blue infrastructure, built areas, regulatory and institutional governance, perceptions, and individual values (Andersson *et al.*, 2019). It is pertinent to reiterate that the perception of individuals as beneficiaries affected ecosystem services. Therefore, the PLS-SEM software applied in this study showed statistically significant relationships between the four socioeconomic characteristics of respondents and the nine sub-variables of UGS visits. This was confirmed by the fact that 7 out of the 36 hypotheses developed were supported at a significance of P = 0.001 level and 2 at P = 0.05 as presented in Table 5 and Fig. 4. It was discovered that the age criterion was positive and significantly related to the behavioral intention to travel outside Jakarta solely for activities in UGS as indicated by the significant path coefficient with mean = -0.048, T = 2.181, SD = 0.022, and $p < 0.05$. Furthermore, education criteria were positively and significantly related to just started exercising and recreation activities constructs of the UGS as presented by the path coefficient for the "just started exercising" with mean = -0.083, T = 2.867, SD = 0.029, and $p < 0.01$ and just started recreation activities with mean = -0.088, T = 3.197, SD = 0.027, and $p < 0.01$. The findings also showed that occupational status had a positive and significant relationship with exercise frequency, recreation frequency, and recreational location with $p < 0.01$. Moreover, the average monthly income was also found to be positively and significantly related to exercise routine, recreation routine, and traveling outside Jakarta solely for UGS activities with path coefficient (Mean = 0.101, T = 3.273, SD = 0.031, $p < 0.01$), (Mean = 0.077, T = 2.566, SD = 0.031, $p < 0.05$), and (Mean = 0.087, T = 2.634, SD = 0.033, $p < 0.01$), respectively.

Table 5 shows the relationship between respondents' characteristics and UGS visitation which was assessed using SmartPLS software at 95% and 99% confidence levels. It was discovered that the age variable only had a significant influence on the willingness to travel outside Jakarta for UGS activities. There was also a substantial correlation between the education level and the initiatives to start exercising and recreational activities in UGS during the pandemic. Moreover, occupational status had three significant correlations with exercise frequency, recreation frequency, and recreational location. The average monthly income was also observed to have a significant relationship with exercise frequency, recreation frequency, and willingness to travel outside Jakarta for UGS activities during the period. It is important to note that aligning the role and accessibility of UGS with institutions, perceptions, and stakeholder interests is the main

Table 5: The relationship between characteristics of respondents and visitation to UGS using PLS-SEM

No.	Characteristics of respondents	Visitation to UGS	Mean	SD	T Statistics	*p* Values
1.	Age	Just started exercising	-0.034	0.024	1.361	0.174
		Just started recreation	-0.034	0.022	1.511	0.131
		Exercise routine	0.001	0.023	0.031	0.975
		Recreation routine	0.022	0.024	0.880	0.379
		Exercise frequency	0.018	0.024	0.702	0.483
		Recreation frequency	0.012	0.027	0.421	0.674
		Exercise location	0.037	0.022	1.592	0.112
		Recreational location	0.030	0.024	1.201	0.230
		Traveling outside Jakarta solely for activities in UGS	-0.048	0.022	2.181	0.030**
2.	Educational level	Just started exercising	-0.083	0.029	2.867	0.004***
		Just started recreation	-0.088	0.027	3.197	0.001***
		Exercise routine	0.005	0.029	0.258	0.796
		Recreation routine	0.020	0.028	0.718	0.473
		Exercise frequency	0.013	0.031	0.368	0.713
		Recreation frequency	0.001	0.030	0.016	0.987
		Exercise location	0.006	0.031	0.160	0.873
		Recreational location	0.017	0.030	0.596	0.552
		Traveling outside Jakarta solely for activities in UGS	0.020	0.028	0.712	0.477
3.	Occupational status	Just started exercising	0.006	0.025	0.221	0.825
		Just started recreation	0.006	0.024	0.300	0.764
		Exercise routine	0.041	0.025	1.661	0.097
		Recreation routine	0.048	0.026	1.867	0.062
		Exercise frequency	-0.061	0.023	2.634	0.009***
		Recreation frequency	-0.093	0.023	4.003	0.000***
		Exercise location	-0.033	0.025	1.337	0.182
		Recreational location	-0.088	0.025	3.494	0.001***
		Traveling outside Jakarta solely for activities in UGS	-0.033	0.024	1.351	0.177
4.	Average monthly income	Just started exercising	0.033	0.029	1.121	0.263
		Just started recreation	0.046	0.029	1.541	0.124
		Exercise routine	0.101	0.031	3.273	0.001***
		Recreation routine	0.077	0.030	2.566	0.011**
		Exercise frequency	-0.057	0.031	1.807	0.071
		Recreation frequency	-0.029	0.030	0.909	0.364
		Exercise location	0.000	0.029	0.031	0.975
		Recreational location	-0.008	0.030	0.250	0.803
		Traveling outside Jakarta solely for activities in UGS	0.087	0.033	2.634	0.009***

Note: **indicates $p \leq 0.05$; *** indicates $p \leq 0.01$

challenge to its utilization. This was confirmed by the findings of Payne *et al*. (2002) that age had a strong influence on the preference and behavior of people in UGS. It was further stated that people with higher educational levels had more understanding of the need to prioritize health improvement during the COVID-19 pandemic. It was stated in previous studies found that UGS has the ability to reduce stress and also offers different psychological and emotional benefits during health crises. This can be stated to be the reason most respondents traveled outside Jakarta to enjoy UGS in the suburbs despite social restrictions and the trend was found to have been influenced by age and average monthly income. Furthermore, the patterns of direct correlations between the characteristics of respondents and their motivations for UGS visitation are presented in Fig. 4. It was discovered that UGS visitation was encouraged by the educational level as indicated by the percentage of those that started exercising and recreation at these spaces at the

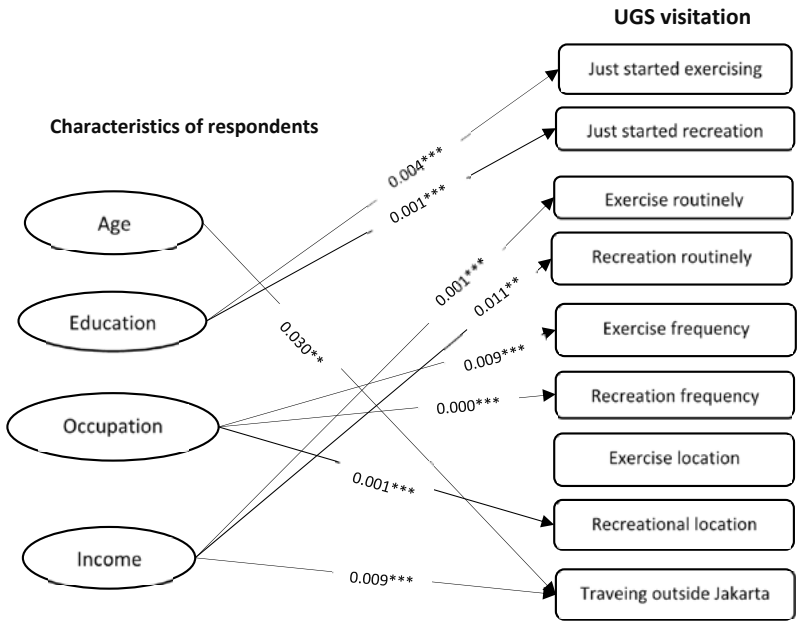

Fig. 4: The patterns of direct correlations between the characteristics of respondents and motivations for UGS visitation (** $p < 0.05$; *** $p < 0.01$)

time. Age and education level also had a significant influence on the willingness to travel outside Jakarta solely to visit UGS as well as to start exercising and engaging in recreational activities. Meanwhile, the occupational status sub-variable had three significant correlations with exercise frequency, recreation frequency, and recreational location. The average income level also had a strong effect on exercise frequency, recreation frequency, and willingness to travel outside Jakarta solely to visit UGS. The findings also showed that respondents within the productive age started exercising, engaging in outdoor recreation, and traveling outside Jakarta to visit UGS during the COVID-19 pandemic.

The PLS-SEM software applied for data analysis showed statistically significant relationships between the proximity of residential areas to UGS with three criteria out of nine associated with UGS visits, except for the distance of 500–1,000 m from the residential area to the park. It was also noted that only 1 out of the 36 hypotheses developed was supported by significant relationships at P = 0.001 level and 2 at P = 0.05 as indicated in Table 6 and Fig. 5. Moreover, the < 500 m distance from residence to an urban forest was observed to have a positive and significant influence on only the visitation to a recreational location with the path coefficient recorded to be mean = -0.052, T = 2.106, SD = 0.024, and $p < 0.05$. The 500–1,000 m distance from residence to an urban forest was also discovered to have a positive and significant effect on the "just started exercising" variable of the UGS visitation with the path coefficient reported to be mean = -0.069, T = 3.108, SD = 0.022, and $p < 0.01$. It was also discovered that the < 500 m distance from the residence to the park positively and significantly affected the recreation frequency with a path coefficient of mean = 0.068, T = 2.404, SD = 0.028, and $p < 0.05$. Table 6 shows the relationship between the proximity of the residential areas to the UGS and the visitation tendency using PLS-SEM software at 95% and 99% confidence levels. It was discovered that the respondents living less than 500 m and 500–1,000 m to the urban forest had a significant correlation with recreational locations and to start exercising when they visit UGS. The findings further showed that those living less than 500 m from the park also had a significant correlation with exercising location but those at 500–1,000 m did not. Another observation showed that the respondents in residence located less than 500 m from the urban forest significantly correlated with UGS's recreational activities while those within a radius of 500–1,000 m had a better substantial relationship with

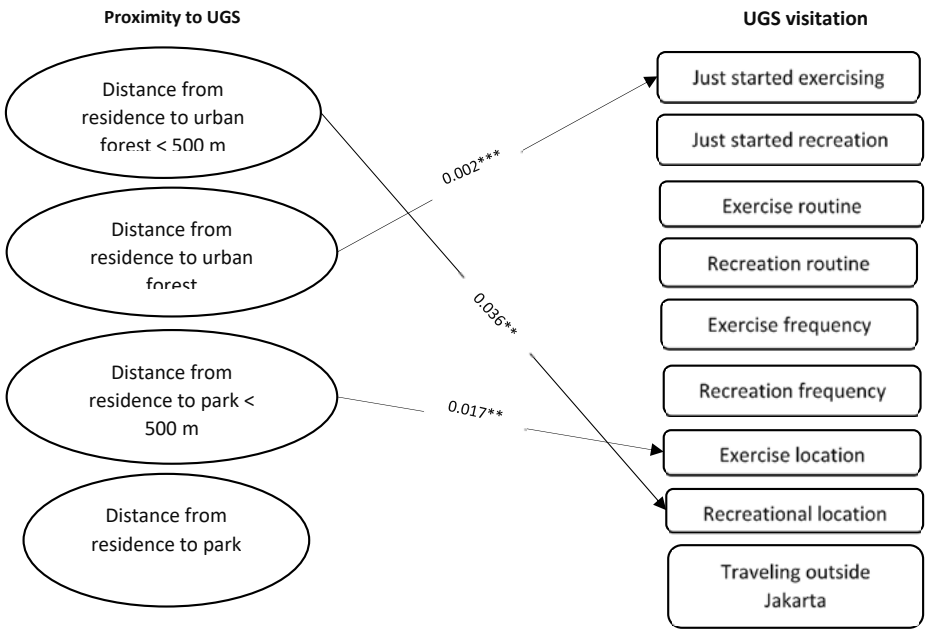

Fig. 5: The patterns of direct correlations between residential proximity to UGS and motivations for UGS visitation (** $p < 0.05$; *** $p < 0.01$)

the initiative to start exercising during their visits to UGS. The findings showed that those residing less than 500 m from the park had a significant correlation with a visit to exercise locations but those within 500–1,000 m had none. These findings differ from the observation of Lopez *et al.* (2020) that visitors were motivated to visit New York's green spaces due to social distance and accessibility. Meanwhile, it was discovered that the proximity to parks and urban forests in Jakarta barely correlated with the motivation to visit as indicated in Fig. 5. This means accessibility is not a significant factor in utilizing UGS in Jakarta. This is similar to the findings of Yen *et al.* (2017) that accessibility is not significant to the usage of UGS through a study conducted in Phnom Penh, Cambodia, a developing country, using PLS-SEM. However, it is contrary to the results presented by Andersson *et al*. (2019) and Honey-Rosés *et al.* (2020) that accessibility has a psychological relationship with the perceptions of users. It is also different from the findings of Wang *et al*. (2015a), Koohsari *et al*. (2013), Wang *et al.* (2015b), and Byrne *et al.* (2009) that one of the factors influencing behavioral intention to use UGS is accessibility.

There was a decrease in activity at UGS during the pandemic compared to the pre-pandemic period (Setiowati *et al.,* 2022) but there was an increase in the number of visits during the post-pandemic period because the parks and urban forests previously closed were opened as observed in Tebet Eco Park. This park is under the management of JCCG in Tebet District, South Jakarta, and has become the favorite for residents and visitors from outside Jakarta since the beginning of the "new normal". It was discovered that the residents had a very high enthusiasm after Eid as observed from the City Parks and Forestry Agency data that the number of visitors on May 8, 2022 reached 47,052 people and this was higher than the figures before the COVID-19 pandemic. It is pertinent to note that the UGS in Jakarta, such as parks and urban forests, were re-opened by JCCG on October 23, 2021 in line with the reduction of the social restrictions to level 2 based on Governor Decree Number 1245 of 2021. President Joko Widodo also officially lifted the social restriction policy in Indonesia on December 30, 2022. Meanwhile, it was discovered that there was an increase in the number of visits to UGS during post COVID-19 pandemic because the parks and urban forests were opened but there is a need for further study on this trend. Previous study showed that the restriction policy affected the standard of living of the people in Jakarta (Pribadi *et al.*, 2020). This is indicated by the reduction in their purchasing power which led to the provision of social assistance

Table 6: The relationship between proximity to UGS and visitation to UGS using PLS-SEM

No.	Proximity to UGS	Visitation to UGS	Mean	SD	T Statistics	*p* Values
1.	Distance from residence to urban forest < 500 m	Just started exercising	0.034	0.026	1.355	0.176
		Just started recreation	0.025	0.025	0.986	0.324
		Exercise routine	0.019	0.025	0.787	0.431
		Recreation routine	-0.004	0.023	0.111	0.911
		Exercise frequency	-0.041	0.025	1.622	0.105
		Recreation frequency	-0.044	0.026	1.739	0.083
		Exercise location	-0.021	0.024	0.842	0.400
		Recreational location	-0.052	0.024	2.106	0.036**
		Traveling outside Jakarta solely for activities in UGS	0.005	0.026	0.149	0.881
2.	Distance from residence to urban forest 500–1,000 m	Just started exercising	-0.069	0.022	3.108	0.002***
		Just started recreation	-0.034	0.023	1.487	0.138
		Exercise routine	0.030	0.027	1.187	0.236
		Recreation routine	0.016	0.027	0.680	0.497
		Exercise frequency	0.018	0.026	0.734	0.463
		Recreation frequency	-0.003	0.026	0.068	0.946
		Exercise location	0.009	0.025	0.438	0.662
		Recreational location	-0.002	0.026	0.081	0.935
		Traveling outside Jakarta solely for activities in UGS	-0.024	0.026	1.051	0.294
3.	Distance from residence to park < 500 m	Just started exercising	-0.043	-0.043	-0.043	-0.043
		Just started recreation	-0.017	0.024	0.699	0.485
		Exercise routine	0.000	0.027	0.018	0.986
		Recreation routine	-0.002	0.029	0.098	0.922
		Exercise frequency	0.052	0.027	1.929	0.054
		Recreation frequency	0.047	0.026	1.706	0.089
		Exercise location	0.068	0.028	2.404	0.017**
		Recreational location	0.023	0.026	0.829	0.407
		Traveling outside Jakarta only for activities in UGS	-0.045	0.026	1.687	0.092
4.	Distance from residence to park 500–1,000 m	Just started exercising	-0.008	0.028	0.282	0.778
		Just started recreation	-0.006	0.027	0.126	0.900
		Exercise routine	-0.003	0.027	0.153	0.878
		Recreation routine	-0.002	0.026	0.135	0.893
		Exercise frequency	0.016	0.028	0.561	0.575
		Recreation frequency	0.037	0.027	1.341	0.180
		Exercise location	0.039	0.027	1.468	0.143
		Recreational location	0.045	0.026	1.693	0.091
		Traveling outside Jakarta solely for activities in UGS	-0.014	0.029	0.501	0.617

Note: **indicates $p \leq 0.05$; *** indicates $p \leq 0.01$

by the government because of the declining national income and slow economic growth. The policy also led to the closure of all UGS in Jakarta and drew much criticism because several people were still commuting and most companies were still operating. The study conducted by Caraka *et al.* (2020) showed significant differences in the mobility of the population before and during the COVID-19 pandemic in Indonesia. It was reported that there were severe economic losses and real disruption of activities in all walks of life due to large-scale restrictions. Moreover, the information in the mass media showed the emergence of a new habit in Jakarta which was in the form of an increase in the number of cyclists during the pandemic but the trend has reduced recently. Venter *et al*. (2020) also reported a similar situation in Oslo, Norway, with the visits to UGS for recreation and sports observed to increase during the lockdown by 291% and 324%, respectively. This means the social restrictions policy implemented in Jakarta to reduce the usage of UGS did not stop the motivation of some people to engage in recreational and exercise activities in these spaces.

A previous study showed that knowledge, practice, identity, beliefs, views, literature, and art influence the design of UGS planning (Kenter, 2016). It was also noted that subjective perception is an interpretation of the benefits of ecosystem services shaped by culture and institutions (Andersson *et al*., 2019). This simply showed that social and cultural characteristics influence the perceptions and preferences of visitors to UGS in Jakarta. Therefore, the city government needs to conduct an evaluation and assessment of UGS management in order to accommodate the needs and expectations of the users in the planning design. This is necessary because public space is one of the urban elements that give character and identity to a city and also provides socioeconomic, environmental, and cultural functions to communities.

CONCLUSION

Jakarta has been dealing with the COVID-19 pandemic for roughly three years and the social restrictions and UGS closure policy implemented discouraged visitation to the green spaces in the city. It was discovered that there is no study on the usage of public UGS during the pandemic based on the socioeconomic attributes of the residents and the distance of their residence to parks and urban forests in Indonesia, specifically on a regional scale such as Jakarta Province, despite the fact that the behavior of the people in relation to UGS visitation changed during the period. Therefore, this study applied PLS-SEM analysis to determine the relationship between socioeconomic characteristics and access to UGS to provide empirical evidence needed by city planners in designing parks and urban forests. The results showed that there are substantial and functioning UGS in Jakarta and they were perceived by the residents to be more useful during the COVID-19 pandemic. The same homogenous preferences were also perceived by the community at the administrative city level in Jakarta. The factors observed to be influencing public use of UGS in the city were discovered to include the socio-demographic characteristics of the users and access to the facilities. These characteristics include age, education level, occupational status, and average monthly income level. This study statistically showed that the accessibility to parks and urban forests had only 3 out of the 36 significant associations relates to the utilization of UGS. The finding is contrary to related studies in other countries that accessibility is an important reason for UGS visits. This shows the need to analyze the change in the behavior of people visiting UGS during the COVID-19 pandemic in order to plan and make appropriate policies to ensure sustainable urban development. UGS was empirically confirmed to be a resilient urban infrastructure during a pandemic but Jakarta policymakers and city planners need to further improve the quality of the current UGS to ensure better accessibility and excellent activities. This study only provided the perception of UGS by the residents of Jakarta which is the capital city of Indonesia and this means the results cannot be generalized to other provinces of the country. Therefore, there is a need to conduct further investigation on the use of UGS during the post-pandemic period in Jakarta and other provinces using additional variables. The limitation of this study is the usage of only four variables to represent the socioeconomic characteristics of the respondents and determine their tendency to visit UGS. It is recommended for future studies to focus on analyzing UGS visits using more varied characteristics such as gender and marital status with attention placed on the comprehensive analysis of each factor. The characteristics of public UGS can also be analyzed based on the area, categories, and quality. These are necessary to promote sustainable urban planning and develop resilient UGS in responding to the long-term crisis of the COVID-19 pandemic.

AUTHOR CONTRIBUTIONS

R. Setiowati conducted all the experiments and wrote the manuscript. R.H. Koestoer as the corresponding autor as well, participated in the interpretation of the results and revised the manuscript, K. Mizuno revised the manuscript, and H.S. Hasibuan contributed to the data analysis and revised 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.

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ABBREVIATIONS

%	Percent
COVID-19	Corona virus disease 2019
CO_2	Carbon dioxide
ha	Hectare
JCCG	Jakarta Capital City Government
km	Kilometers
km^2	Kilometer square
No.	Number
m	Meters
m^2	Meter square
p	Probability
$people/km^2$	People/ square kilometer
PLS-SEM	The partial least square structural equation model
SD	Standard deviation
SmartPLS	Smart partial least square
T	T Statistic
UGS	Urban green space
USD	United States Dollar
WHO	World Health Organization

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Podcasts

CASE STUDY

Developing a composite-based constitutive model for municipal solid waste

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ABSTRACT

BACKGROUND AND OBJECTIVES: Harmful ruptures and instabilities in landfills in recent years have highlighted the importance of studying the municipal solid waste and its behavior. These instabilities mostly occur in the landfill of developing countries where waste materials are degradable and saturated. The behavior of waste and its ingredients are unknown as the main reasons for such instability. The main goal of this study was to better predict the behavior of landfills and unknown materials in municipal solid waste to prevent the environmental disasters.

METHODS: A cylindrical specimen was modeled and subjected to triaxial test loading conditions using the finite element method. Also, fresh waste, as a waste sample with a specific composition, was investigated. Using the optimization method, the constants of the presented equation were obtained and the basic model of stress strain was presented based on composite theory.

FINDINGS: The whole models for predicting the waste behavior were presented based on the behavior models of soils. This was carried out by the theory of composite materials, which was used for the first time in this study. At the strains of less than 30 percent, a well agreement was observed between the results of the numerical and the present methods. Also, at confining stresses less than 100 kiloPascal, the root mean square of the relative error percentages between the total stresses obtained from the present model and another model was less than 10 percent. At higher confining stresses, this amount was in the range of 10 – 20 percent.

CONCLUSION: The results of this study were compared with those of the experimental data in previous models to verify the proposed model. The model proved to be capable of simulating and predicting the municipal solid waste behavior under various loading conditions efficiently. The results implied that assuming the municipal solid waste as composite material was reasonable and could be extended to future studies.

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INTRODUCTION

In recent decades, landslides in landfills have caused significant problems, including severe environmental pollution, urban infrastructure destruction, landfill destruction, and, most importantly, human casualties (Bezerra de Araujo Filho et al., 2014; Faitli et al., 2015; Malave et al., 2020). For instance, the rupture of the Payatas landfill in the Philippines killed about 300 people. The increase in waste leachates due to rainfall is the main cause of such ruptures (Merry *et al.,* 2005). Various methods are provided for separation, collection and storage of waste (Teshome *et al.,* 2023). While the needs of society have been to prevent these incidents and improve environmental safety, the existing knowledge regarding the behavior of such materials is very limited (Stark *et al.,* 2009; Kumar *et al.,* 2009; Chelliapan *et al.,* 2020). Predicting the behavior of materials is particularly important in various sciences such as mechanics (Liu *et al.*, 2021; Savaedi *et al.*, 2022), civil engineering (Sadrnejad *et al.*, 2019; Thakur *et al.*, 2022; Sarmah *et al.*, 2021), biological experiments (Zhang *et al.*, 2021; Holzapfel *et al.*, 2021; Hoursan *et al.*, 2021), and other applications. Compared to soil mechanics, the mechanical behavior of landfills has been subjected to many studies for the last three decades (Carvalhod *et al.*, 2004; Machado *et al.*, 2002; Kolekar *et al.*, 2016). Most of the researchers have attempted to investigate the mechanical behavior of such materials using the laboratory investigations (Gharabaghi *et al.*, 2008; Zekkos *et al.*, 2005; Collin *et al.*, 2018). The desired deformations have been obtained in the laboratory studies conducted using the triaxial test and by applying stress on the waste samples (Keramati *et al.*, 2018; Shariatmadari *et al.*, 2017). Due to the great complexity of parameters influencing waste behavior, there are still many unknown features in this area, as waste materials show different behaviors compared to other materials (Keramati *et al.*, 2019; Alidoust *et al.*, 2021). Considering the necessity for more accuracy in the prediction of such materials, numerical studies have also been carried out in recent years (Karimpour-Fard *et al.*, 2021; Raviteja *et al.*, 2021). Eventually, studies on municipal solid waste (MSW) materials grew in number, and researchers became more familiar with the mechanical properties of waste materials using laboratory data. As a result, the need to predict waste behavior and the role of its mechanical properties received greater attention (Shariatmadari *et al.*, 2009; Shariatmadari *et al.*, 2014). Some studies showed that many parameters, such as environmental conditions, confining stresses, age and temperature of the waste, had a great impact on the behavior of these materials (Karimpour-Fard *et al.*, 2011; Alidoust *et al.*, 2018; Abu-Qdais *et al.,* 2020). Researchers also attempted to have a better prediction of landfills by considering the influencing parameters (Carvalhod *et al.*, 2004; Keramati *et al.*, 2020). One of the early behavioral models presented for modeling the waste mechanical behavior is the model suggested by Machado *et al*. (2008) who established their model based on triaxial experiments (Machado *et al.*, 2008). These researchers considered waste as a two-phase substance. The first phase was supposed to be its paste-like segment originating from leachates, and the second phase was considered to be fiber. In their model, they did not consider the effect of the ratio of the waste constituents on its mechanical behavior; they relied on Young's modulus as a constant variable through time. Machado *et al*., (2010) attempted to upgrade their experiment by studying fresh and 4-year-old waste. In another study, they validated their model by laboratory findings and applying a correction compensating for changes in the shape of waste materials. Nevertheless, they merely compared their model with laboratory results without predicting a comprehensive behavioral model (Machado *et al.*, 2017). However, the presented model significantly differed from laboratory results, especially in high strains. They explained that abnormal pulses were observed in some cases in high volumetric strains, which had not been presented in the related charts. The model used by these researchers was the low-total soil model (Machado *et al.*, 2017). Babu *et al*. (2010) investigated the waste behavior model using a modified low-total soil model. They assessed fresh, 1.5-year-old artificial waste (Marques *et al.*, 2003). In their model, the obtained strains were assessed according to the soil behavior models, and the total strain of waste was calculated by summing up all the strains. The model showed a good agreement with laboratory results in small deformations and low strains. In high strains, and especially when there was an extreme all-around pressure, inconsistency was observed between the model and the laboratory results. This could be attributed to ignoring the deformations caused by

waste particles. The main problem of the model was considering a soil model for the whole substance. Krase *et al.* (2007) also used the theory of fibers and paste to propose their behavioral model. Later, Zhang *et al.* (2010) investigated the waste behavior model by dividing waste into different phases. Considering a modified low-total behavioral model for the leachate phase of waste and a one-dimensional plastic model for the solid phase of waste, they presented a new model by combining the two models. The new model had several fundamental weaknesses, including one-dimensionality, lack of suitable agreement with laboratory results in significant deformations, and, as acknowledged by the researchers, inappropriateness of the finite element model used (Zhang *et al.*, 2010). Excluding the enclosed pressures of the pore water and ignoring the elastoplastic method could also be mentioned as other limitations of the model proposed by Zhang *et al.* (2010). Applying the soil model for waste causes errors in the deformation of its internal particles and alterations in the enclosed volumes. Fang *et al.* (2016) using the laboratory results of Babu *et al*. (2010) investigated waste behavior by applying the theories of biological, elastic, plastic, and consolidation strains. They presented their findings employing a parameter that improved biological strains (Feng *et al.*, 2016). Hanke *et al.* (2017) compared the prediction models of waste behavior and deformations occurring in the landfill mass. This comparison was not made in the same conditions, and the results obtained from landfill strains were compared as a whole. As already mentioned, various parameters, including temperature variations of waste due to various internal interactions, can affect waste behavior (Shariatmadari *et al.*, 2014; Machado *et al.*, 2010). Hubert *et al.* (2016) comprehensively studied the strain-stress properties of waste. They presented the findings of previous studies in a graph, demonstrating that the shape changes of the landfill occurring over time at different temperatures. According to their study, temperature varied considerably during the first year of landfilling and gained more stability after about five years. Magyar *et al.* (2015) investigated the temperature changes of waste in a landfill. They poured waste into a metal box with a volume of 1.5 cubic meters and assessed the effect of temperature changes on waste components. Kumar *et al.* (2020) also studied waste behavior using the theory of soft soils. They presented their model by analyzing the behavior of soft clay, as an alternative for waste, and summing up the strains caused due to elastic, elasto-plastic, and sliding events occurring over time. They used the Moher-Colmb method to examine the strains created in a trench over 40 years. The results showed no specific pattern for changes in waste settlement over time and an increase in waste settlement over time (Kumar *et al.,* 2020). The theory of composite materials in soil mechanics is used to investigate the behavior of reinforced soils and soil-plastic composite materials. The study conducted by Consoli *et al.* (2007) is among such experiments. They used the combination of sand and fiber as a composite material. Using the direct shear test, creating tension in the fiber, and mathematically calculating fiber movement in soil samples, they obtained the stress-strain diagram. They finally found that the angle of fiber placement in soils profoundly impacted the composite material's behavior. Chengizadeh and Nikraz (2011) also performed direct shear tests on composite soil samples to assess the effects of these materials on soil resistance. Investigating the effects of fiber on clay soils, they witnessed shape changes in the soil after altering the percentage of fiber from 0 percent (%) to 2%. In another study, Cheng *et al.* (2015) used a combination of sand and fiber was as a composite material. They obtained the stress-strain diagram by calculating fiber orientation in the soil sample. The famous models for the prediction of the MSW behavior are shown in Table 1.

Referring to Table 1, in most of the studies, to better predict the waste behavior, MSW has been divided into two parts: paste and fiber. Behavioral models of soils are considered as the primary model, and the fiber part is added to it. These two parts have special characteristics and behaviors, but their combination may have different characteristics. Due to the complexity of waste material, it can lead to significant errors. The presented models have been compared and evaluated using the laboratory results obtained by the own researchers, and no comprehensive behavioral model for waste has been presented so far. Since MSW is composed of unknown materials and is very different from soil, the composite theory can be helpful in providing a unified model for evaluating the behavior of waste. In this study, the theory of composite materials was used to assess the behavior of MSW. The waste

Table 1: Comparision between the developed constitutive models for predicting the MSW behavior

Model	Basic model	Compared with	Equation provided	Assumptions
Zhang *et al.*, 2010	Soil (cam clay and modified cam clay)	Modified cam clay and their analytical solution	×	Principal stress, one dimensional solution
Machado *et al.*, 2017	Soil (modified cam clay)	Cam clay and their triaxial test	Yes	Fresh MSW, 4-years old MSW, variable E
Babu *et al.*, 2010	Soil (modified cam clay)	Strain of the landfill and their triaxial test	Yes	Fresh MSW, 1.5 years old MSW, creep biodegradation
Feng *et al.*, 2016	Soil and Babu *et al.*, 2010 model.	Model of Babu *et al.*, 2010	Yes	Biodegradation parametric study constant E
Krase *et al.*, 2007	Soil (modified cam clay)	Strain of a specific landfill and their triaxial test	×	Time dependent creep biodegradation, variable E
Present study	Composite material	Babu *et al.*, 2010 and Feng *et al.*, 2016	Yes	Fresh MSW, variable E, parametric study, variable confining stress

sample was simulated as a cylindrical shape using the finite element method for better simulation and comparison of results. Subsequently, the processes of presenting and predicting the waste behavioral model and requirements for such predictions were explained. The primary stress-strain relationship was presented for these materials using the theory of composite materials. The aim of this study was to use composite theories in predicting waste behavior. Development of this theory in future studies is suggested, as it can lead to better prediction of MSW and investigation of more parameters. This study and its numerical simulation were carried out using the data of Tehran landfill in Iran in 2021.

MATERIALS AND METHODS

In this study, fresh MSW was initially modeled using ANSYS software and then subjected to triaxial loading using the material composite theory. Moreover, a macroscopic viewpont of composite materials was used to predict the total MSW behavior via composite-based constitutive models. After obtaining stress-strain results, the constants of composite equation were determined based on optimization methods and laboratory results. The results were compared with those of other studies to validate the equation.

Stress-strain response

ANSYS is commonly used to obtain the stress-strain response for the MSW. As shown in Fig. 1, to predict the behavior of these materials, a cylindrical sample with a diameter of 20 centimeter (cm), height of 40 cm, and fixed boundary condition at one side was simulated according to the experimental specimen conditions of the triaxial tests and subjected to compressive stress. The same confining pressure was applied to the surrounding area of the sample. The pressure started from zero and continued until the confining pressure stress was reached. After the confining pressure reached the desired value, an additional stress was applied to the upper surface of the cylinder and this value continued linearly. The strain corresponding to the stress applied on the upper surface of the sample was also obtained.

After modeling, the waste sample was subjected to meshing using tetrahedral meshes. In order to render the experiments independent of the mesh size, their dimensions were subjected to sensitivity analysis (Table 2). During the sensitivity analysis, the all-around pressure was considered as 100 kPa, and the additional stress was calculated as 150 kiloPascal (kPa). The most significant mesh value was obtained as 0.025 milimeter (mm), which was an acceptable error rate (i.e., <1%), and it was used as a basis for further calculations.

As already mentioned, the used model was composite behavior considering the elastoplastic and plastic waste behaviors and the Voce's theory (Voce 1948). In this model, which relies on the Drager-Prager hardening model, the changes in plastic strains have

Fig. 1: The MSW sample modeling

Table 2: Results of the mesh sensitivity análisis

Maximum size of mesh sides (mm)	Strain	Relative error (%)
4	0.019	-
2	0.0224	15.1
1	0.0240	6.8
0.5	0.0150	4.1
0.025	0.0248	0.7

a linear relationship with rebound stresses. Using an equation relating rebound stresses to plastic strains, Armstrong and Frederik convert the linear kinematic hardening model of Prager to a non-linear model. The first kinematic hardening model was presented by Prager, in which the changes in plastic strains had a linear relationship with rebound stresses using Eq. 1 (Zhang *et al.* 2015; Voce 1948).

$$dX = \frac{2}{3} C d\varepsilon^{\cdot} - \gamma X dp \quad (1)$$

Where, C and gamma are the constants of the material; and *dp* represents the cumulative plastic strain that has a non-linear relationship with stress. This behavioral model has been used for composite materials, and the graphs obtained from this model consist of three segments: elastic, elastoplastic, and plastic. According to the results, the waste seemed to first act in an elastic manner, then entered the elastoplastic phase, and underwent hardening. The strain-stress function of waste can be calculated from the relationships in this theory using Eq. 2 (Zhang *et al.* 2015; Voce 1948).

$$\sigma = a + b_1\left(1 - \exp\left(\frac{-\varepsilon_p}{c_1}\right)\right) + b_2\left(1 - \exp\left(\frac{-\varepsilon_p}{c_2}\right)\right) \quad (2)$$

Where, a, b_1, b_2, c_1, and c_2 are the constants of the equation; and σ and ε_p represent stress and strain, respectively. This composite model was used as a reference for modeling the waste behavior. This equation was coded parametrically and modified by optimization methods to be used as a behavioral model for the simulated sample. Stress was calculated at any point of strain based on the laboratory results using numerical methods. Considering the minimal calculation error, the best prediction for waste behavior was projected. After applying all-around stress and reaching balance in the sample, the linear axial loading was executed, and the stress continued up to 30% strain. Strains greater than 30% reflect extensive deformations, which were not investigated in this study. The used fresh waste and its features are shown in Table 3. The amount of fiber combined with the laboratory sample was obtained as 12.5%. The

Table 3: Mechanical properties of MSW

$E\,(\mathrm{M}\,P\,\mathrm{a})$	$\gamma_s\,(k\,\mathrm{N/m^3})$	λ	κ	φ
200	19	0.136	0.0065	19

Table 4: Physical properties of MSW

Details	Percentage (%)
Cloth	3.66
Tuber	0.38
Stone	11.47
Plastic	21.13
Glass	3.91
Iron	3.16
Wood	4.86
Paper	16.2
Paste	35.23

physical properties of the waste are demonstrated in Table 4.

According to Table 4, MSW was composed of various materials. All ingredients had different properties with different behaviors. Application of the theory of composite materials led to an integrated prediction of waste considering the behavior of all the materials used.

RESULTS AND DISCUSSION

Using the theory of composite materials and numerical simulation of MSW, as a triaxially loaded specimen, the behavior of fresh MSW was investigated. The Voce's theory was used as a theory of composite materials (Zhang *et al.,* 2015; Voce 1948). Moreover, the results of the triaxial test performed by Shariatmadari *et al.* (2009) were utilized in the constitutive model (Shariatmadari *et al.*, 2009; Machado *et al.,* 2010). To achieve the MSW stress-strain equation, the experimental strain-stress results were compared with the results of the composite method, and the constant parameters of the equation were obtained through optimization. The fiber-free waste was analyzed and then fiber was added to the material. The strain results were used against the strain parameter for a better comparison. The paste material was considered as soil and loaded using the Cam Clay Model (MCC). As shown in Fig. 2, with the increase of deviatoric stress in the sample the strain occurred at higher stresses.

According to various modeling strategies and previous studies, Young's modulus is among the factors influencing the waste behavior. By maintaining the limiting stress constant, Young's modulus changed in the model (Fig. 3). According to the diagram, the changes in Young's modulus were more noticeable at lower strains; these changes did not considerably affect the strain-stress results.

After modeling the paste-like material of the waste, the modeled fibers were subjected to tension by applying stresses of 100, 200, and 300 kPa, showing plasticity (Fig. 4). According to the stress-strain diagram, the more stress is applied to the fiber, the closer it becomes to flowing.

Laboratory results and the composite equation were achieved using the optimization methods for obtaining the constants of the strain-stress equation related to MSW. Laboratory conditions must be similar to allow for comparison of the obtained equation with the models proposed in previous studies. This was initially fulfilled by coding the existing models using the similar inputs. The relation for the stress-strain was obtained using Eq. 3. (Babu *et al.*, 2010). In this part, the simulation was done at a constant temperature and for fresh MSW.

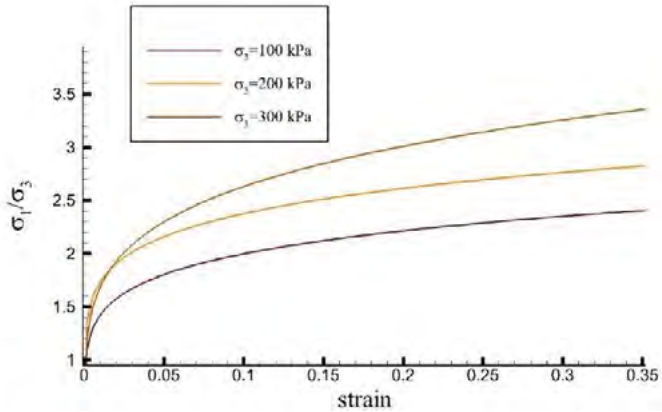

Fig. 2: Stress-strain diagram for MSW without fiber at confining stresses of **100**, **2**00, and **3**00 kPa

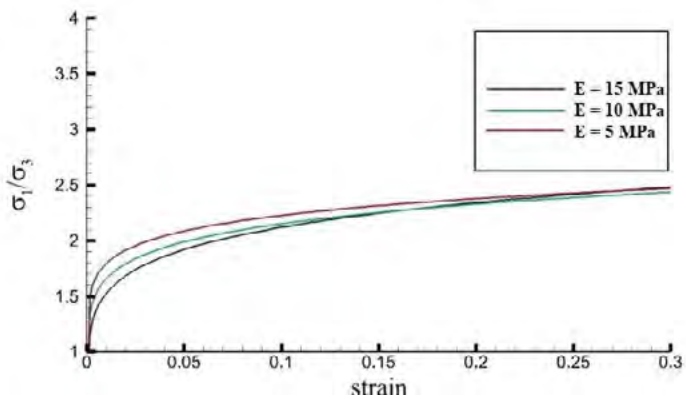

Fig. 3: Stress-strain diagram for MSW at Young's moduli of 5, 10, and 15 MPa

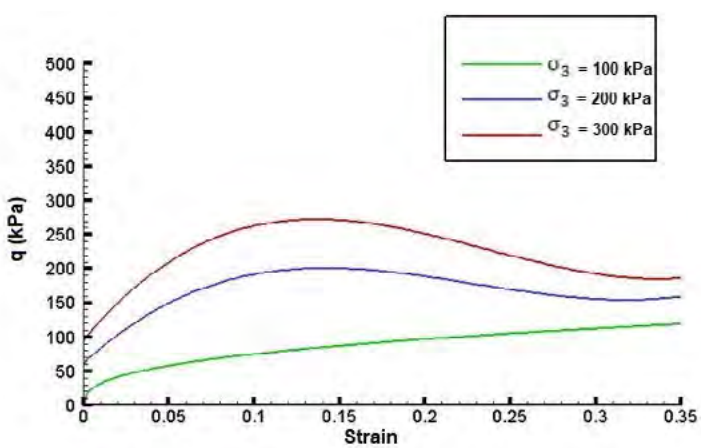

Fig. 4: Stress-strain diagram for fiber at confining stresses of 100, 200, and 300 kPa

$$q = a_1\left(1 - e^{(b\varepsilon)}\right) + a_2\left(1 - e^{\left(-\frac{\varepsilon}{c2}\right)}\right) + a_1 \quad (3)$$

$$a_1 = -2.79 - 0.07\sigma_3 \ - 0.0002\sigma_3^2$$
$$b_1 = 0.24$$
$$b_2 = -9.17\sigma_3$$
$$c_1 = -0.27$$
$$c_2 = -0.27$$

Where, ε denotes the MSW total strain; and σ_3 is the confining stress. According to Eq. 3, the total stress was relative to changes in the deviator stress, and the strain was dependent on the confining stress. One of the models available for MSW is the one developed by Babu *et al*. (2010). This model was compared with the model proposed in this study. In their model, the sum of sudden strains, degradation, biological and consolidation strains was used to predict the waste behavior using soil models.

The model proposed by Babu *et al.* (2010) showed a good agreement with their laboratory results regarding small deformations and strains (Fig. 5). Inconsistencies were observed between the present model and the results reported by Babu *et al.* (2010) at high strains, especially at high confining stresses. The errors for this comparison were 10.1%, 8.2%, and 25.36 % at confining stresses of 50 kPa, 100 kPa, and 200 kPa. This could be attributed to ignoring the deformations caused by waste particles. The main problem of the model proposed by Babu *et al.* (2010) is relying on a soil model for the whole materials. Moreover, the soil model considers the impact of pore water pressure as a total and effective stress difference. Another comparison was also made between the results obtained in the present study and the findings of Feng *et al*. (2016) as shown in Fig. 6. In the cam-clay model, MSW has been divided into two parts: fiber and paste. This model, by combining the deformations caused by creep, biological, elastic and plastic, provides a relationship for strain stress. The difference between Feng's model and Babu's model is the extension of biological deformation of waste and consideration of a parameter for its deformation. As illustrated in Fig. 6, both models showed a good agreement and the existing difference was due to the errors in both methods. Obviously, as the confining stress increased, hardening occurred in the MSW and the slope of the graph increased. The root mean squares of the relative error percentages between the total stresses obtained from the presented model and Eq. 3 were 6% and 11.2% for confining stresses of 100 and 200 kPa, respectively.

The correlation between the results showed the validity of the presented formulation. One of the

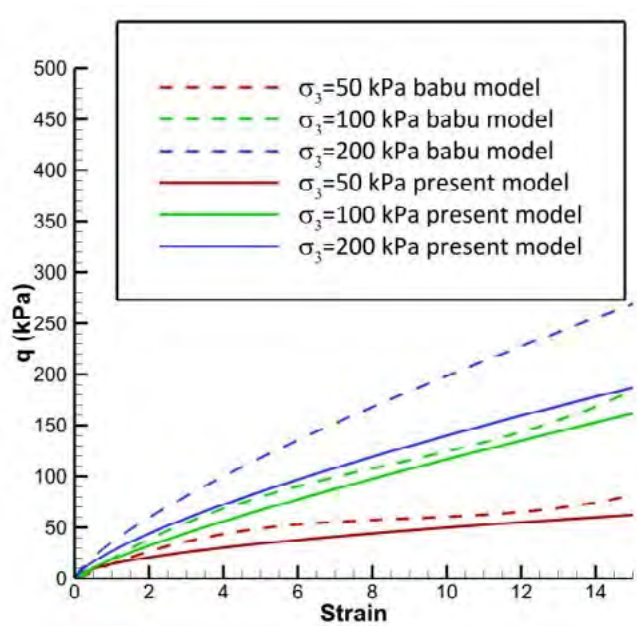

Fig. 5: Comparison of the presented model and the Babu's model at confining stresses of 50, 100, and 200 kPa

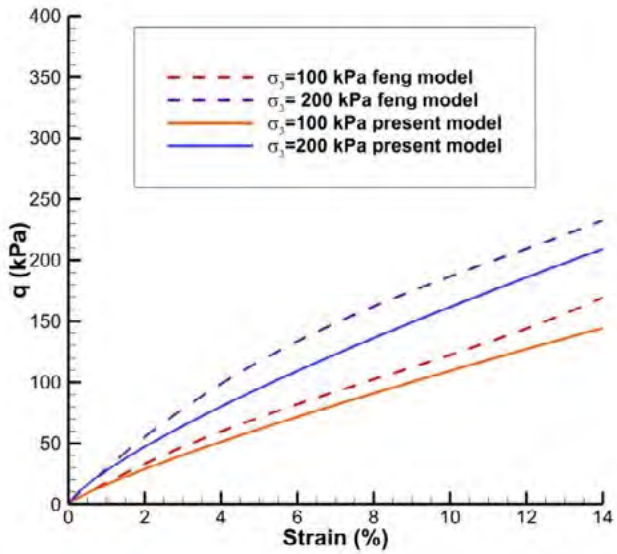

Fig. 6: Comparison of the presented model and Feng's model at confining stresses of 100 and 200 kPa

reasons for these errors might be calculation errors or the influence of other effective factors in the stress-strain responses which were not taken into account. This correlation could be due to numerous interactions of waste during large deformations, having a great impact on the behavior of waste. At the beginning of the diagram up to a strain of about 2%, there was more consistency between the results indicating the behavior of MSW at low strains. The lower confining stress in the MSW led to lower errors. A reason for this adaptation could be the lower impact of stress on the chemical and physical interactions within the MSW. At the lower levels of stress, biological changes in the MSW were less, and the MSW interactions were less than the ones observed at higher stress levels. In soil mechanics, the solid matter and the pore water are assumed to be incompressible, and the soil's volume change is only due to the volume change of the voids. For MSW, the situation seems much more complex. The volumetric strains of MSW under compression stem from not only the movement of the waste particles, but also from the compression of the compressible particles themselves. The MCC behavioral model has been used in most of the behavioral models for predicting the waste behavior. Due to the compact nature of the waste particles, application of the MCC model may cause a lot of errors. Waste particles also deform when deviator stress is applied. In the composite theory, the waste material is considered to be uniform and all the deformations are measured.

CONCLUSION

Predicting the behavior of MSW has been one of the most challenging topics in human science. Since there is no behavioral model to predict the behavior of this material, many researches are currently being conducted. MSW is composed of different materials, and the interaction of these materials greatly impacts their behavior. Studies on the behavioral model of waste mostly consider it as a soil material (not a single material) which has a combination of plastic materials. In soil mechanics, all the soil elements are assumed to be incompressible and their behavior is quite different from that of MSW. Using the theory of composite materials, the overall deformation of MSW was calculated. In this model, the MSW behavior was simplified and mainly characterized by confining stress, which significantly affected the behavior prediction. The rendered simulation showed the large effect of the confining stress on the waste behavior. At the beginning of the diagram up to a strain of about 2%, there was more consistency between the results indicating the MSW behavior at low strains. The lower confining stress in the MSW led to lower errors. At stresses less than 100 kPa,

the error percentage was obtained to be less than 10%. The interaction of internal waste materials was also less. In higher stresses, the hardening in the waste behavior was more visible. Since almost all the researchers have compared the results of the behavioral models with their own results, no comprehensive prediction of MSW behavior has been provided so far. In this study, after determining the stress-strain relationship for waste, the results were compared with the findings of other studies. Although, almost acceptable initial results were obtained in this study, it is still recommended to predict the behavior of this complex material considering other influential parameters in future studies using the composite theory. This model has been developed for fresh MSW but it can be used for early prediction of landfill behavior. Moreover, it was concluded that the use of finite element simulations and considering all the influencing parameters in the MSW behavior could lead to a more accurate understanding of these materials.

AUTHOR CONTRIBUTIONS

M.R. Yousefi, the first author, contributed to the simulation performing, data analysis, interpreting the results, and preparing the manuscript. A. Noorzad, as the corresponding author, the second author, and the first author supervisor, conceptualized the research and checked the manuscript for English language error. M.J. Mahmoodi participated in the revision of the manuscript.

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

%	Percent
ε	Strian
ε_p	Plastic strain
γ	Constant of equation
γ_s	Specific weight
σ	Stress
σ_3	Confining stress
ϕ	Internal frictional degree
κ	Constant of the Camclay equation
λ	Constant of the Camclay equation
a	Constant of equation
b1	Constant of equation
b2	Constant of equation
C	Constant of equation
c1	Constant of equation
c2	Constant of equation
cm	Centimeter
$d\varepsilon$	Change in strain
dX	Change in kinematic back stress
dP	Cumulative plastic strain
E	Elastic module
Eq.	Equation
exp	Exponential operator
Fig.	Figure
kN/m^3	Kilo newton per cubic meter

kPa	Kilo pascal
mm	Mili meter
MPa	Mega pascal
MCC	Cam clay model
MSW	Municipal solid waste
q	Total stress
X	Kinematic back stress

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CASE STUDY

Water security assessment framework for deltas of the transboundary river basins

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ABSTRACT

BACKGROUND AND OBJECTIVES: Water security for food production in the deltas of international river basins has become the top concern of the basin countries. Numerous efforts were made to develop frameworks for the assessment of water security at different scales. However, no framework could be directly applied to the deltas of the transboundary basins because they have not fully addressed the characteristics of the deltas. This study aims to develop a comprehensive framework for the assessment of water security for the international river basin deltas and applied it to the Vietnamese Mekong Delta.
METHODS: The water security assessment framework was developed on the basis of the concept of water security defined by the United Nations Water following the "Driving forces-Pressure-State-Impact-Response" approach. The developed framework is then used to evaluate the water security conditions for 22 subregions of the Mekong Delta.
FINDINGS: The proposed water security assessment framework comprises the following six dimensions: water resources, domestic water supply, water for economic development, water-related disasters, ecological and environmental protection, and water governance, which contain 21 indicators and 5 sub-indicators. The results of applying this framework to the Mekong Delta showed that the overall water security conditions in most subregions in 2018 were only at the medium level. The degree of water security in flood season is higher than that in the dry season. The main reasons that lead to the medium-level water security of the region have been identified, including high dependence on external water resources (more than 90%) and transboundary water cooperation between the basin countries and rather low water productivity in economic sectors. The study suggests that improvement in transboundary water cooperation and water productivity would help enhance future water security in the Mekong Delta.
CONCLUSION: Assessment of the water security for the deltas of the transboundary river basins requires a comprehensive assessment framework. The framework developed in this study was successfully applied to the case of the Vietnamese Mekong Delta. The proposed framework will help policymakers of the Mekong riparian countries to monitor the impact of the basin development plans and policies on water security conditions jointly and determine appropriate solutions to enhance water security for the basin.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
42	6	2

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INTRODUCTION

Water is essential for life and all human development activities. It is also a renewable resource; however, the world's water resource is finite and is facing the risk of degradation and depletion due to overexploitation and climate change (Kim *et al*., 2018; Kumar, 2018; Arab *et al.,* 2021; Zhu *et al*., 2022). Thus, ensuring water security for human life and ecosystems is the top concern of all countries worldwide (Mekonnen and Hoekstra, 2016; Thang *et al.,* 2019). The world has 276 transboundary river basins, crossing 151 countries and territories, and is home to more than 40 percent (%) of the global population (De Strasser *et al.,* 2016; Dennis and Grady, 2022). The total flow of transboundary rivers accounts for approximately 54% of the total flow of all rivers in the world. Ensuring water security in these river basins is substantially more challenging than those within the territory of a country due to their dependence on the spirit of cooperation of the riparian countries in the basins. Within the river basins, the deltas are the most special areas with common features that are located at the most downstream parts of the basins and generally adjacent to the sea. These deltas receive a considerable amount of water and sediment from the upstream parts yearly and have become the main food production areas of the countries in the basins. The delta regions are currently facing remarkable challenges of climate change and increased water exploitation and utilization in the basin, which markedly affects the water and food security of countries worldwide (Hong, 2020). Policymakers often raise the questions of how to assess and quantify the water security for the deltas of the transboundary river basins, where the water is managed by different countries with various interests and priorities in water use, and what appropriate decisions must be taken to ensure water security for the region. Many studies have been conducted on water security at different scales, including global (Gain *et al.,* 2016), country (Makin *et al*., 2013; Holmatov et al, 2017; Koontanakulvong and Doungmanee, 2015; Marttunen *et al*., 2019), city (Jensen and Wu, 2018; Hoekstra *et al.*, 2018; Aboelnga *et al*., 2019), basin (Dong and Liu, 2014; Babel and Shinde, 2018; Giri *et al.,* 2018; Mui, 2018; Hatmoko *et al*., 2020; Babel *et al*., 2022), and delta scales (Dou *et al*., 2021). These studies developed water security assessment frameworks with their indicators and applied them according to their purposes. For example, Makin *et al*. (2013) proposed a framework of indicators for assessing national water security comprising five dimensions (household water security, productive economy, urban water security, environment water security, and resilience to water-related hazards) but disregarded the governance dimension and transboundary feature of water resources. Jensen and Wu (2018) developed a framework specifically for the assessment of domestic water security, which comprises four dimensions (resources, access, risks, and governance), and applied to the case of Singapore and Hong Kong. Similarly, Aboelnga *et al*. (2019) also worked on an urban water security framework and attempted to incorporate the transboundary–imported water dependency ratio into the framework. Babel and Shinde (2018) proposed a framework for water security assessment at the basin scale comprising five dimensions (water availability, water productivity, water-related disasters, watershed management, and water governance) and applied it to water security assessment in river basins in Thailand (Babel *et al*., 2022). Mui (2018) aimed to develop a framework for the assessment of water security for the Ma river basin in Vietnam. Although applied to transboundary river basins (some river basins in Thailand are transboundary), the frameworks proposed in the studies of Babel *et al.* (2022) and Mui (2018) did not consider the transboundary factors. At the delta scale, Dou *et al*. (2021) developed a method for assessing the water security for the river basin deltas. The framework contains only three dimensions (water resources security, environmental security, and exploitation and utilization potential) and was applied to the case of the national river basin delta (Yangtze River Delta, China). Many attempts have been made to develop frameworks for the assessment of water security at different scales. However, no framework could be directly applied to the deltas of the transboundary basins because they have not fully addressed the characteristics of such delta regions. Some studies focused only on one aspect of the deltas, such as domestic water security (Jensen and Wu, 2018; Aboelnga *et al*., 2019), while others focused on several aspects of the river basin deltas, but still have not fully captured the characteristics of the delta region, especially the transboundary factors in their frameworks (Babel and Shinde, 2018; Mui, 2018; Dou *et al*., 2021; Babel *et al*., 2022). A more

comprehensive assessment framework than the previous ones is required due to the special features of the transboundary basin deltas. This study aims to propose a water security assessment framework for the deltas of transboundary river basins by taking the Mekong Delta of Vietnam as the case study. The specific objectives of the study are as follows: i) to measure the water security in the Mekong Delta, ii) to identify the main factors that most affect the water security, and iii) to propose solutions for improvement of the water security in the region. The water security assessment framework developed in this study will help policymakers and managers monitor and evaluate the impact of the development plans and policies on water security conditions, identify factors affecting water security, and determine appropriate solutions to enhance water security for the deltas for the transboundary river basins. This study has been conducted in the Mekong Delta of Vietnam during 2019 to 2022.

MATERIALS AND METHODS

The Mekong river delta is selected as the pilot site for this study because it is the delta of the international river basin and plays a crucial role in food security for Vietnam. This river delta is also one of the deltas in the world that are most vulnerable to sea level rise. The section below will describe the details of the pilot site and the development method of the water security assessment framework for the region.

Description of the pilot site

The Mekong River delta flows through the following six countries: China, Myanmar, Laos, Thailand, Cambodia, and Vietnam, with a total length of 4763 kilometer (km) and a total annual flow of approximately 446 billion cubic meter (m^3). The Mekong River Basin covers an area of approximately 810,000 square kilometer (km^2) and is home to more than 70 million people, who are mainly dependent on agriculture and aquaculture (MRC, 2018). The Mekong Delta of Vietnam is the last part of the Mekong River Basin (Fig. 1). With a total natural area of approximately 3.96 million hectares (ha), this river basin is home to over 22% of the country's total population. The Mekong Delta receives a considerable amount of water (approximately 440 billion m^3/year) and sediment (160–165 million tons/year) from the upper part of the Mekong River Basin yearly (MRC, 2018). With remarkable agricultural potential, the Mekong Delta contributes over 50% of the total food

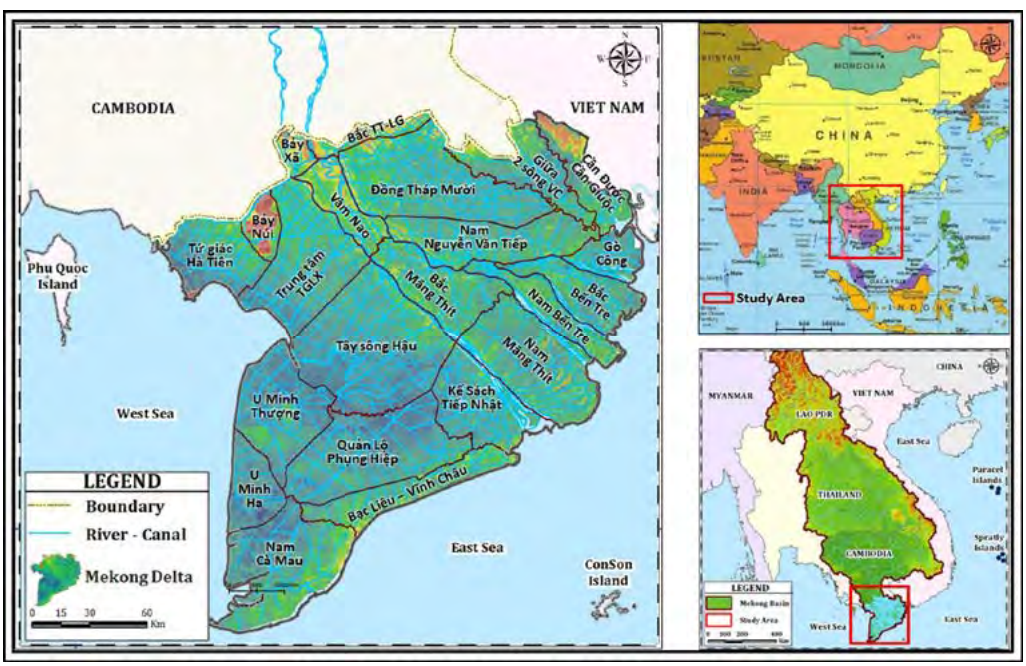

Fig. 1: Geographic location of the study area in the Mekong Delta in Vietnam

products and more than 90% of the country's total rice export (Thang *et al*., 2019). In addition to meeting the domestic demand, the rice product of Vietnam also contributes to feeding approximately 40 million people in Asian and African countries. People living in the delta rely on the Mekong water for water supply, food production, inland transport, and many other services. However, located in the downstream part of the Mekong River Basin, the Vietnamese Mekong Delta increasingly suffers from serious impacts of water-related development activities in the basin and unpredictable effects of faster-than-expected climate change. If these threats are not properly addressed, then the endeavor toward sustainable development and the livelihoods of millions of people living in the area will be severely affected.

Development of water security assessment framework for the Mekong Delta

The development of the framework for the transboundary river basin deltas is based on the frameworks of Mui (2018) and Babel *et al*. (2022) for water security assessment at the basin scale. This approach was conducted by proposing additional indicators and sub-indicators that characterize the special features of the transboundary river basin deltas into their frameworks. The framework built in this study and that of the two other studies rely on the definition of water security (Grey *et al*., 2013; UN-Water, 2013; Loe and Hjornlund, 2008; Wilhelm *et al*., 2022) and follow the "Driving Forces-Pressure-State-Impact-Response" approach, which was widely used in water assessment (Babel and Shinde, 2018; Sun *et al*., 2018; Van Ginkel *et al*., 2018; Lu et *al*., 2022). Following this approach, the degree of water security for the region is characterized by an overall water security index that comprises various water security dimensions. The water security dimensions are selected on the basis of various factors that have impacts on water security and each dimension comprises one or more indicators/sub-indicators, which are selected in accordance with the SMART (Specific, measurable, achievable, relevant, and time-based) criteria (Vachnadze, 2016). Each indicator/sub-indicator is measured by one or more variables.

Calculation of water security indexes/indicators

The parameters are calculated quantitatively or qualitatively based on available data and collected information to compute the water security indexes/indicators for each subregion. These parameters with different units will be normalized on a common scale from 1 to 5 for comparison (Aboelnga *et al*., 2019). The values of each indicator (*I*), dimension (*D*), and overall water security for the delta (*WSI*) are calculated by the weighted method using Eqs. 1, 2, and 3, respectively (Assefa *et al*., 2019).

$$I_{ij} = \sum_{j=1}^{n}\sum_{j}^{m} w_{ijk} S_{ijk} \quad (1)$$

$$D_i = \sum_{j=1}^{n} x_{ij} I_{ij} \quad (2)$$

$$WSI = \sum_{i=1}^{p} y_j D_i \quad (3)$$

Where, *p* is the number of dimensions, *n* is the number of indicators in dimension *i*, *m* is the number of variables for indicator *j*, *w* is the weight given to each variable, *S* is the score of each variable, *x* is the weight given to each indicator, and *y* is the weight given to each dimension. The weight of each variable, indicator, and dimension is determined by logical analysis based on the characteristics and conditions of each delta with close consultation with experts and scientists.

All data and information required for water security assessment were obtained from the General Statistics Office of Vietnam, Provincial People's Committees and their relevant Departments in the Mekong Delta, and relevant research institutes. The data and information on the upstream part of the Mekong River Basin were obtained from the Mekong River Commission Secretariat in Vientiane, Laos. Some secondary data and information were taken from previous studies and other data were obtained from the surveys (questionnaires).

RESULTS AND DISCUSSION

The authors developed the water security assessment framework for the Mekong Delta considering its specific conditions and applied it to calculate the water security indexes for 22 subregions based on the method described above.

The boundaries of the subregions are zoned on the basis of the Mekong Delta Regional Plan in the period 2021–2030 with a vision to 2050 (MPI, 2022). The findings of this study were presented and discussed with the different stakeholders, including the representatives from the relevant government agencies, provincial authorities in the Mekong Delta, research institutes, scientists, and technical experts in various fields, during the course of the study.

Water security assessment framework for the Mekong Delta

The framework is characterized by an overall water security index comprising the following six dimensions (Mui, 2018): water resources, domestic water supply, water for economic development, water-related disasters, ecological and environmental protection, and water governance. Considering the selection of indicators, in addition to those proposed by Mui (2018) and Babel *et al*. (2022), the authors introduced five additional indicators and three sub-indicators to different dimensions to capture the characteristics of the Mekong Delta. The rationales for the selection of these additional indicators are as follows. Water resources in the Mekong Delta are highly dependent on external sources and seasonally varied. Therefore, one indicator reflecting the dependence on the external water source and two sub-indicators reflecting the intra-annual variability of the river flow and the capability to resist the variability were added to the water resources dimension. Under the domestic water supply dimension, two indicators considering the efficiency of the centralized water supply systems and the affordability of water use tariff were supplemented. As inland waterway transport is one of the important modes of transport, one indicator of water use for inland waterway transport was introduced considering the water economic activities dimension. For the agricultural sector, in addition to agricultural use efficiency, the authors proposed one additional sub-indicator to ensure water security and reflect the proportion of irrigated arable land. Under the water governance dimension, one indicator of transboundary water cooperation among the basin countries was finally added. Overall, the proposed framework comprises 21 indicators and 5 sub-indicators. The framework captures the impacts of climate change through various indicators under the dimensions of water resources, water economic activities, water-related disasters, and environmental and ecological system protection. Table 1 presents the detailed water security assessment framework for the Mekong Delta. The ranges and scores for water security indicators were adopted for the Mekong Delta using some selected values that have been established in previous studies (Makin *et al*., 2013; Mui, 2018; Aboelnga *et al*., 2019). For new indicators and sub-indicators that are specific to the Mekong Delta, the ranges and scores were proposed in close consultation with the managers, experts, and scientists. Table 2 shows the results of the ranges and scores adopted for the Mekong Delta.

Considering the weights of the water quality indexes and indicators, similar to approaches adopted by Mui (2018), three dimensions related to water resources, domestic water supply, and economic activities have a direct impact on water security, and the weight of each dimension is chosen to be 0.2. The environmental and ecological system protection dimension has an indirect impact and is of high importance for water security; therefore, the weight is 0.15. Two dimensions related to water-related disasters and water governance have an indirect impact on water security; therefore, the weight is 0.125. The sum of the weights given to 6 dimensions is equal to 1. Similar to Aboelnga *et al*. (2019), the water security index in this study is also divided into the following five levels: (1) poor (index <1.5), (2) low (index score: 1.5–2.5), (3) medium (index score: 2.5–3.5), (4) high (index score: 3.5–4.5), and (5) very high (index score >4.5). Tables 1 and 2 are used to calculate the water security index for each dimension in this study.

Water resources dimension

The calculation results show that the water availability in all subregions is remarkably high, with the annual average water volume per capita in all subregions ranging from 20,000 to 24,000 m^3/person/year. This value is substantially higher than the threshold applied worldwide (1700 m^3/person/year) (Srinivasan *et al*., 2017; Singh, 2018) and also higher than that of other river basins in the regions (Mui, 2018 and Babel *et al*., 2022). Despite a high value of water availability, the overall water security index for the water resources dimension for each subregion ranges only from 2.7–2.9, which indicates a "medium" level of water security (Fig. 2a). The aforementioned

Table 1: Water security assessment framework for the Vietnamese Mekong Delta

No	Dimension/indicator	Sub-indicator	Variable	Methods of calculation
I. Water resources dimension, D_1				
1	Water availability, $I_{(1,1)}$		Per capita water availablity (m^3/person/year)	Annual renewable water resources/population (Aboelnga *et al.*, 2019; Oluwasanya *et al.*, 2022)
2	Water resilience, $I_{(1,2)}$	Intra-annual variability, $I_{(1,2,1)}$	Intra-annual flow coefficient of variation	$C_v = \frac{\sqrt{\frac{\sum_i^n (Q_i - Q_0)^2}{n-1}}}{Q_0}$,
		Inter-annual variability, $I_{(1,2,2)}$	Inter-annual flow coefficient of variation	where C_v is the intra-and inter-annual flow coefficient of variation, Q_i is the water discharge at month/year *i*, Qo is the monthly/yearly average discharge, and *n* is the number of months in year/number of years for calculation (Makin *et al.*, 2013)
		Water storage, $I_{(1,2,3)}$	Duration that water storage can meet the water demand (days)	(Total water amount stored in rivers/canals and exploitable groundwater quantity in Delta)/Daily water demand (Jensen and Wu, 2018, Park et al., 2022)
3	Dependence on external water sources, $I_{(1,3)}$		Proportion of external water sources (%)	(Amount of water originating from foreign countries/Annual renewable water resources) × 100% (Makin *et al.*, 2013)
II. Domestic water supply dimension, D_2				
4	Accessibility to clean water, $I_{(2,1)}$		Proportion of clean water accessed by users (%)	(Number of clean water accessed by users/total population) × 100% (Assefa *et al.*, 2019)
5	Accessibility to clean water from centralized water supply systems, $I_{(2,2)}$		Proportion of clean water accessed by users from centralized water supply systems (%)	(Clean water accessed by users from centralized water supply systems/total population) × 100% (Assefa *et al.*, 2019)
6	Efficiency of the centralized water supply systems, $I_{(2,3)}$		Proportion of water losses from centralized water supply systems (%)	(Total water losses/Total water supply amount from the centralized water supply systems) × 100% (Mui, 2018)
7	Water sanitation, $I_{(2,4)}$		Proportion of households with hygienic latrines (%)	(Number of households with hygienic latrines/Total number of households) × 100% (Mui, 2018)
8	Affordability of water use tariff, $I_{(2,5)}$		Proportion of the cost for domestic water use (%)	(Annual payment for domestic water use/ total annual income of the users) × 100% (Assefa *et al.*, 2019)
III. Water economic activities dimension, D_3				
9	Water consumption for economic activities, $I_{(3,1)}$		Proportion of water used for economic sectors (%)	(Total amount of water used by water consumptive economic sectors/total exploitable water amount) × 100% (Mui, 2018)

Continued Table 1: Water security assessment framework for the Vietnamese Mekong Delta

No	Dimension/indicator	Sub-indicator	Variable	Methods of calculation
10	Water use for agriculture, $I_{(3,2)}$	Irrigated area, $I_{(3,2,1)}$	Proportion of irrigated arable land (%)	(Irrigated arable land/Total arable land) × 100% (Makin *et al.*, 2013)
		Agricultural use efficiency, $I_{(3,2,2)}$	Agricultural use efficiency, United States dollars per cubic meter (USD/m^3)	Total financial value of the agricultural products/Total amount of water used in agricultural production (Makin *et al.*, 2013)
11	Water use for inland waterway transport, $I_{(3,3)}$		Insecure duration for navigation (days)	Determined on the basis of the number of days when the daily average water depth in the river/channel is less than the specific water depth required for each category of the river/channel (Proposed by Authors)
12	Water use for industry, $I_{(3,4)}$		Industrial use efficiency (USD/m^3)	Total financial value of the industrial products/Total amount of water used for the industry (Makin *et al.*, 2013)
IV. Water-related disasters dimension, D_4				
13	Capacity to cope with disasters, $I_{(4,1)}$		Gross Domestic Product (USD/person/year)	Method of calculation of the Gross Domestic Product (Mui, 2018)
14	Drought factor, $I_{(4,2)}$		Proportion area of drought (%)	(Drought-affected area/Total arable land) × 100% (Babel and Shinde, 2018)
15	Flood factor, $I_{(4,3)}$		Proportion area of flooding (%)	(Flood-affected area/Total arable land) × 100% (Babel and Shinde, 2018)
16	Saltwater intrusion factor, $I_{(4,4)}$		Proportion area of saltwater intrusion (%)	(Saltwater intrusion affected area/Total arable land) × 100%
V. Environmental and ecological system protection dimension, D_5				
17	River flow for the environment and the ecosystem, $I_{(5,1)}$		Difference of river flow with the acceptable minimum monthly natural flow during each month of the dry season (%)	(Difference of river flow with the acceptable minimum monthly natural flow during each month of the dry season/Acceptable minimum monthly natural flow during each month of the dry season) × 100% (Proposed by Authors)
18	Water quality factor, $I_{(5,2)}$		Water quality index for environment and ecosystem	Water quality index method (Călmuc, 2018; Mui 2018)
19	Upstream development activity, $I_{(5,3)}$		Impacts of upstream development activity	Mathematical models (MRC, 2017)
VI. Water governance dimension, D_6				
20	Water resource management in the deltas, $I_{(6,1)}$		Implementation of integrated water resources and river basin management	Interview and consultation with managers, experts, and scientists (Mui, 2018)
21	Transboundary cooperation on water management, $I_{(6,2)}$		Implementation of transboundary cooperation on water management	Interview and consultation with managers, experts, and scientists (Proposed by Authors)

Table 2: Ranges and scores of water security indicators adopted for the Mekong Delta

No	Indexes/ Indicators	Variables	1	2	3	4	5	References
I. Water resources dimension, D_1								
1	$I_{(1,1)}$	Per capacity water availability (m^3/person/year)	<500	500–800	800–1000	1000–1700	>1700	Aboelnga *et al.*, 2019
2	$I_{(1,2,1)}$	Intra-annual flow coefficient of variation	>0.4	0.4 – 0.31	0.3 – 0.21	0.2 – 0.1	<0.1	Proposed by Authors
3	$I_{(1,2,2)}$	Inter-annual flow coefficient of variation	>0.4	0.4 – 0.31	0.3 – 0.21	0.2 – 0.1	<0.1	Mui, 2018
4	$I_{(1,2,3)}$	Duration that water storage can meet the water demand (days)	<1	1–15	16–30	31–60	>60	Proposed by Authors
5	$I_{(1,3)}$	Proportion of external water sources (%)	>60	60 – 40	40 – 20	20 – 10	<10	Aboelnga *et al.*, 2019
II. Domestic water supply dimension, D_2								
6	$I_{(2,1)}$	Proportion of clean water accessed by users (%)	<40	40–60	61–80	81–90	91–100	Mui, 2018
7	$I_{(2,2)}$	Proportion of clean water accessed by users from centralized water supply systems (%)	<60	60–70	71–80	81–90	91–100	Mui, 2018
8	$I_{(2,3)}$	Proportion of water losses from centralized water supply systems (%)	>40	40 – 31	30 – 21	20 – 5	<5	Proposed by Authors
9	$I_{(2,4)}$	Proportion of households with hygienic latrines (%)	<60	60–70	71–80	81–90	91–100	Mui, 2018
10	$I_{(2,5)}$	Proportion of the cost for domestic water use (%)	>2.1	2.1 – 1.21	1.2 – 0.81	0.8 – 0.5	<0.5	Proposed by Authors
III. Water economic activities dimension, D_3								
11	$I_{(3,1)}$	Proportion of water used for economic sectors (%)	>70	70 – 41	40 – 31	30 – 20	<20	Mui 2018
12	$I_{(3,2,1)}$	Proportion of irrigated arable land (%)	<60	60–75	76–85	86–95	96–100	Proposed by Authors
13	$I_{(3,2,2)}$	Agricultural use efficiency (USD/m^3)	<0.1	0.1–0.2	0.2–0.35	>0.35–1	>1	Mui 2018
14	$I_{(3,3)}$	Insecure duration for navigation (days)	>7	5–7	3–4	1–2	<1	Proposed by Authors

Continued Table 2: Ranges and scores of water security indicators adopted for the Mekong Delta

No	Indexes/ Indicators	Variables	1	2	3	4	5	References
15	$I_{(3,4)}$	Industrial use efficiency (USD/m^3)	<2.0	2–5.5	5.6 – 20	21–50	>50	Makin *et al.*, 2013
IV. Water-related disasters dimension, D_4								
16	$I_{(4,1)}$	Gross Domestic Product (USD/person/year)	<516	516–1035	1035–4085	4085–12,614	>12,614	Mui, 2018
17	$I_{(4,2)}$	Proportion area of drought (%)	>40	40 – 21	20 – 11	10 – 5	<5	Mui, 2018
18	$I_{(4,3)}$	Proportion area of flooding (%)	>40	40 – 21	20 – 11	10 – 5	<5	Proposed by Authors
19	$I_{(4,4)}$	Proportion area of saltwater intrusion (%)	>40	40 – 21	20 – 11	10 – 5	<5	Proposed by Authors
V. Environmental and ecological system protection dimension, D_5								
20	$I_{(5,1)}$	Difference of river flow with the acceptable minimum monthly natural flow during each month of the dry season (%)	<(−20)	(−20) – 0	0–5	6–20	>20	Mui, 2018
21	$I_{(5,2)}$	Water quality index for environment and ecosystem	0–25	26–50	51–75	76–90	91–100	Mui, 2018
22	$I_{(5,3)}$	Impacts of upstream development activity	All mainstream dams and tributary dams, and water diversion works constructed	All mainstream dams (except Kratie and Sambo) and tributary dams constructed	Development at the 2018 level	Only tributary dams	No development	Proposed by Authors
VI. Water governance, D_6								
23	$I_{(6,1)}$	implementation of integrated water resources management (IWRM) and integrated river basin management (IRBM)	Still, traditional water management applied; not yet transferred to the IWRM and	IWRM and IRBM were applied at the initial stage; no significant results were achieved.	IWRM and IRBM comprehensively implemented; River Basin Organization established	RBO has an appropriate structure and good results gained from the IWRM and IRBM implementation	RBO has an appropriate structure and excellent results gained from the IWRM and IRBM	Mui, 2018

Continued Table 2: Ranges and scores of water security indicators adopted for the Mekong Delta

No	Indexes/ Indicators	Variables	1	2	3	4	5	References
			IRBM approaches		and initially operated		implementation	
24	$I_{(6,2)}$	transboundary cooperation on water management	No bilateral and multilateral cooperation mechanisms established	Only multilateral cooperation mechanisms were established, but poor cooperation results were still achieved	Bilateral and multilateral cooperation is established, but not all legal and institutional instruments are in place; some results of cooperation achieved	Bilateral and multilateral cooperation established all legal and institutional instruments are in place; good results of cooperation gained	Bilateral and multilateral cooperation established all legal and institutional instruments are in place; very good results of cooperation gained	Proposed by Authors

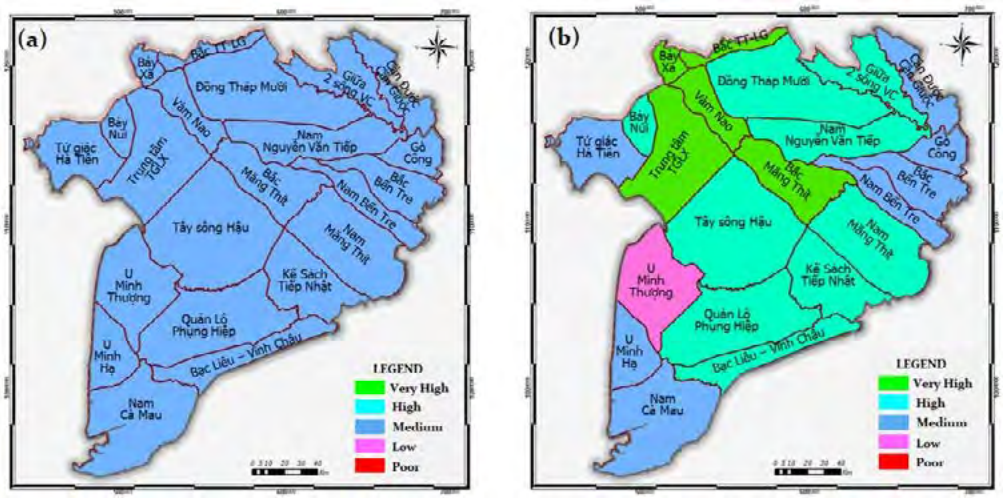

Fig. 2: Maps showing the overall water security index of (a) the water resources dimension and (b) the domestic water supply dimension for each subregion in 2018

results are mainly due to the high dependence of the water resources in the Mekong Delta on external sources (more than 90%), the uneven distribution of the water resources during the year (coefficient of intra-annual variation approximately 0.8), and the relatively smaller water storage in the subregions compared to the total water demand.

Domestic water supply dimension

The overall water security index for the domestic water supply dimension shown in Fig. 2b indicates that 14 of the subregions (more than 60%) located along the Mekong River have a high and very high level of water security. In these subregions, more than 80% of the population can access clean water from state-owned and private water supply systems. The remaining subregions with medium and low domestic water security levels have a substantially limited number of water supply plants because they are located far from the Mekong water. Despite this condition, the water sanitation situation in the region is very good, where 80% of the subregions have a high and very high percentage of households with hygienic latrines. The payment for domestic water use is relatively low (from 0.7–1 USD/person/month), which is equal to approximately 0.5%–1% of the average monthly income. This finding indicates that the water fee is quite affordable for users in all subregions. This phenomenon is also remarkably similar to the case of the Ma river basin in Vietnam (Mui, 2018).

Economic activities dimension

The overall water security index shown in Fig. 3a indicates a medium-level water security for economic activities in most subregions (13/22). Similar to the case of the Ma river basin in Vietnam (Mui, 2018), river basins in Thailand (Babel *et al.*, 2022), and Rafsanjan Plain in Iran (Bagheria and Babaeian, 2020), in the Mekong Delta, agriculture is the largest water user among the economic sectors. People living in the Mekong Delta still apply wet rice cultivation, which consumes considerable amounts of water, while the rice price is usually low. This condition leads to low water use efficiency in agricultural production. The condition for the navigation sector varies across the subregions (10/22 subregions) with a low and poor level of water security. The main reason identified is due to the heavy sediment deposition of the rivers and canals in these subregions and lack of the resources for frequent dredging. Regarding the industry, water security is in a better condition than that of the agricultural and navigation sectors.

Water-related disasters dimension

The overall water security index shown in Fig. 3b reveals that only five subregions have low- to medium-level water security and the remaining subregions have a high water security level. This phenomenon is due to the formed system of dikes and embankments of the Mekong Delta with a total length of approximately 13,000 km to prevent saltwater intrusion, high tide, and storm surge for

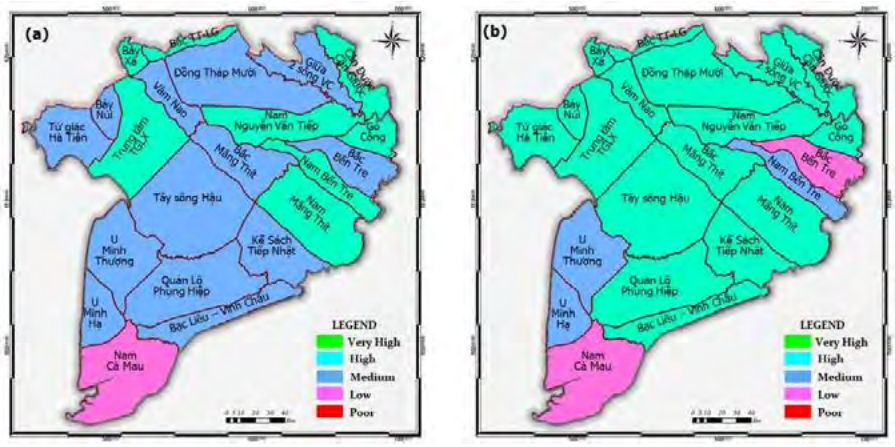

Fig. 3: Maps showing the overall water security index of (a) the economic activities dimension and (b) the water-related disaster dimension for each subregion in 2018

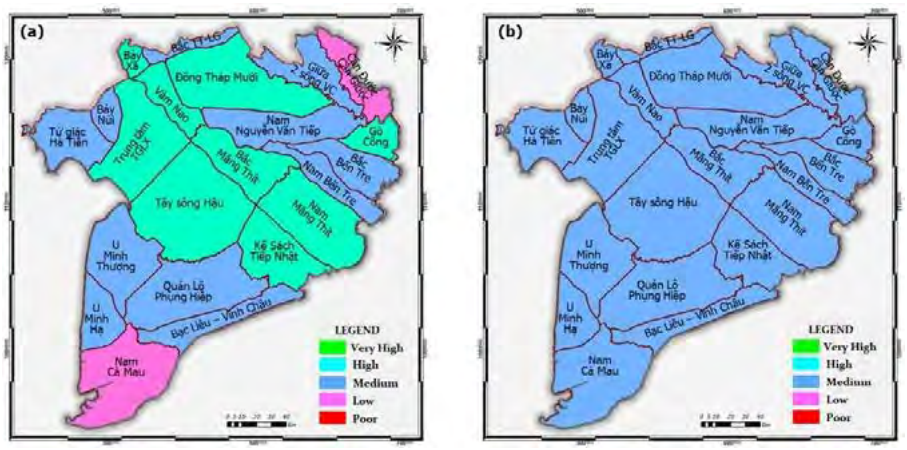

Fig. 4: Maps showing the overall water security index of (a) the environment and ecosystem dimension and (b) the water governance dimension for each subregion in 2018

the coastal areas and avoid August floods to protect summer–autumn rice. Consequently, the damage due to saltwater intrusion and flood is considerably reduced. Those with medium and low water security conditions are the coastal subregions, which are still suffering from saltwater intrusion and drought due to an incomplete dike system and difficulty in accessing the Mekong water.

Environment and ecosystem dimension

The analysis results show that in 2018, the river flow was maintained at high and very high levels in almost all subregions (18/22 subregions) except the coastal subregions. Water quality in most of the subregions is at the medium to the low level. Regarding the development activity in the upper Mekong River Basin, the assessment results show that all subregions of the Mekong Delta are moderately affected at the current level of development (MRC, 2017). Under such circumstances, 9 subregions located along the Mekong River have a high water security level and the remaining (coastal subregions) have medium (11 subregions) and low (2 subregions) levels of water security (Fig. 4a). This phenomenon is due to the tide effects that obstruct the water flow from the canals to the sea and cause the water pollution in the coastal

subregions. The condition of the environment and ecosystem in the Mekong Delta was similar to that of most river basins in Thailand (Babel *et al*., 2022) but better than that in the Ma River in Vietnam (Mui, 2018), where the environment and ecosystem were affected by specific water quality and development activities in the local basin.

Water governance dimension

The results of surveys and assessments of the implementation of IWRM and IRBM in the Mekong Delta and of the transboundary water cooperation in the basin revealed that the water security indicators considering water management results in the delta and the transboundary water cooperation are at the medium level. Consequently, the overall water security index for the water governance dimension is also at the medium level at all subregions of the delta (Fig. 4b), which is similar to the situation of other river basins (Mui, 2018; Babel *et al*., 2022).

Overall water security assessment for the Mekong Delta

Fig. 5a shows the overall water security index computed from the water security indexes of all six dimensions for each subregion in 2018. Despite being a large plain with abundant resources, the water security in most subregions in the Mekong Delta is only at the medium level. Moreover, the water security conditions in the Mekong Delta are

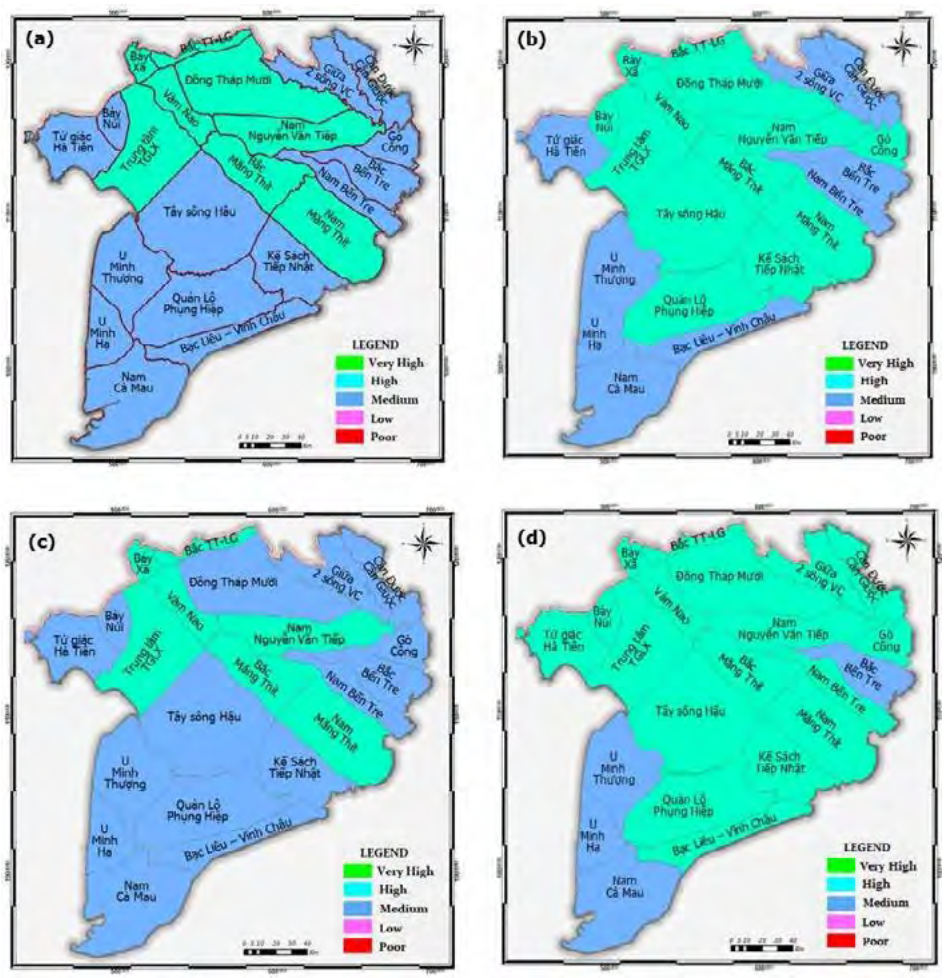

Fig. 5: (a) Overall water security index in 2018; (b) Overall water security index in the 2018 flood season; (c) Overall water security index for the 2018 dry season; (d) Overall water security index in 2018 (based on the methods of Mui, 2018; Babel *et al*., 2022)

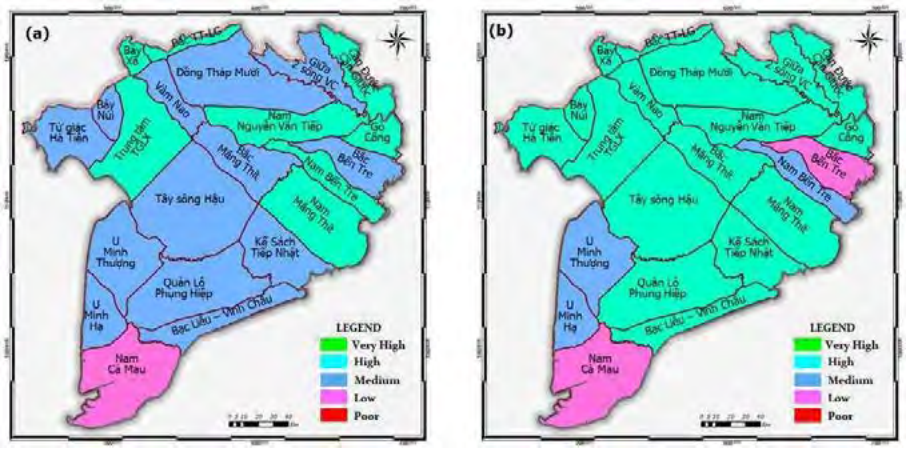

Fig. 6: (a) Overall water security index in 2018; (b) Overall water security index forecasted for 2050

different in the flood and dry seasons due to seasonal variation of the rainfall in the basin and the impact of the upstream reservoir's operation (Figs. 5b and 5c, respectively); the water security in the flood season is better than that in the dry season. This phenomenon is due to the Mekong water serving as the main source for the people, while in addition to the Mekong water, a water source coming from local precipitation is avalaible in the wet season. The water security in the Mekong Delta is governed by external and internal factors. The external factors refer to high dependence on external sources, uneven distribution of water resources, increase in water use by the basin countries, the impact of climate change, and transboundary water cooperation. The internal factors refer to the water use efficiency in the economic sectors, water management, flood, drought, and saltwater intrusion in the Mekong Delta. Similar to the internal factors, external factors also play a crucial role in water security in the Mekong Delta. This phenomenon can be observed by comparing the water security situations of the Mekong Delta obtained by applying the methods of Mui (2018) and Babel *et al.* (2022) (Fig. 5d) and that developed in this study (Fig. 5a). The results indicated that disregarding external factors would lead to inaccurate estimation of the water security condition of the region.

Proposed measures for improvement of water security for the Mekong Delta

Improvement of the water security in the Mekong Delta requires not only a single effort of the Vietnamese government but also joint efforts and cooperation of all basin countries. At the basin-wide level, the riparian countries must strengthen transboundary water cooperation through the existing cooperation frameworks, especially through the Mekong River Commission and the Mekong–Lancang Cooperation. The cooperation should focus on promoting open dialogs among the countries at all levels, strengthening data and information sharing, establishing the basin-wide warning and forecasting system and emergency response mechanisms, and creating the multireservoir operation rules for the entire Mekong mainstream hydropower cascade to regulate the flow between the dry and rainy seasons. At the Mekong Delta level, the solutions should be in a form of combined structural and nonstructural measures. The structural measures would focus on the improvement of the water supply system to the coastal subregions, increase the storage capacity, regular dredging of canals to allow smooth transport of the vessels, and investment in wastewater treatment. The nonstructural measures include application of advanced water technologies for efficient water use and identification of crops that can resist environmental stressors and saline water environment, promoting the implementation of the IWRM and IRBM and roles of the Cuu Long River Basin Committee. The water security conditions forecasted for 2050 would be significantly improved in comparison with that in 2018 based on the Mekong Delta Regional Plan (MPI, 2022), regional development scenarios under the climate change

context in the Mekong River Basin (MRC, 2017), and consideration of all the above-proposed measures (Figs. 6a and 6b). The degree of water security for most subregions of the Mekong Delta would be improved from medium to high level in 2018 to 2050.

CONCLUSION

This study contributed to the development of a water security assessment framework for the deltas of transboundary river basins, specifically for the Mekong Delta of Vietnam, by considering its special feature in the framework. The proposed framework in this study relies on 6 dimensions (including water resources, domestic water supply, water for economic development, water-related disasters, ecological and environmental protection, and water governance), 21 indicators, and 5 sub-indicators. The assessment results of the water security for the Mekong Delta showed that the overall water security conditions in most subregions in 2018 were only at the medium level despite their numerous advantages. The degree of water security in flood season is higher than that in the dry season. The medium-level water security of the region can be mainly attributed to its high dependence on external water resources (more than 90%) and transboundary water cooperation between the basin countries and low water productivity in economic sectors. Therefore, the transboundary factor must not be ignored in the assessment framework because disregarding this factor would lead to inaccurate estimation of the water security condition of the region. The study also suggests that the improvement of transboundary water cooperation, water management plan, and water productivity in the Mekong Delta would help enhance future water security in the region. The main challenge in assessing water security for the transboundary river basin is to obtain sufficient data and information on the upper part of the basin, which can be successfully realized through joint efforts and cooperation of all basin countries. The water security assessment framework developed in this study would introduce an opportunity for the policymakers and managers of the Mekong riparian countries to monitor and evaluate the impact of the basin development plans and policies on water security conditions jointly not only for the Mekong Delta but also for the entire basin, identify factors affecting water security, and determine appropriate solutions to enhance water security for the basin.

AUTHOR CONTRIBUTIONS

T.H. Truong, the corresponding author, was responsible for the development of methodology, data analyses, and draft paper preparation. L.T.T. Nguyen was in charge of overall supervision, study conceptualization, and funding acquisition. T. Pham contributed to the study conceptualization and funding acquisition and calculated indicators under the water economic activities dimension. P.H. Nguyen contributed to the study conceptualization and paper editing and calculated indicators under the dimension of the water-related disaster. D.D. Nguyen contributed to the conceptualization of the study and calculated indicators under the water resources and domestic water supply dimensions. T.M. Vu calculated indicators under the environmental and ecological system protection dimension. Q.T. Nguyen was responsible for data collection and analysis of the water governance dimension.

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CONFLICT OF INTEREST

The author declares 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

%	Percentage
Cv	Intra-and inter-annual flow coefficient of variation
D	Dimension
Đồng Tháp Mười	Name of subregion in the Mekong Delta
GWP	Global water partnership
ha	Hectare
i	Order of dimension
j	Order of indicator
i.e.	That is
IRBM	Integrated River Basin Management
IWRM	Integrated Water Resources Management
km	Kilometer
km^2	Square kilometer
m	Number of variables for an indicator
m	Meter
m^3	Cubic meter
MPI	Ministry of Planning and Investment
MRC	Mekong River Commission
p	Number of dimensions
Q	Water discharge
RBOs	River Basin Organizations
S	Score of each variable
SMART	Specific-Measurable-Achievable-Relevant and Time-based
UN	United Nations
USD	United States dollar
w	Weight for each variable
WQI	Water quality index
WSI	Water security index
x	Weight for each indicator
y	Weight for each dimension

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REVIEW PAPER

Relationship between landscape and river ecosystem services

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ABSTRACT

andscape dynamics are a consequence of population growth, which can degrade river ecosystem services. Since various countries approved the millennium ecosystem assessment, it has inspired researchers to examine the relationship between landscape and river ecosystem services. Therefore, this study aims to summarize previous studies about landscape and river ecosystem services using a systematic literature review. This study referred to the preferred reporting items for systematic reviews and meta-analysis. Data were obtained from six databases of scientific publications such as Scopus, Pubmed, Directory of Open Access Journals, Scilit, Neliti, and Garba Rujukan Digital. The results show that research on this topic has spread worldwide. Landscape data, reflected in land use and land cover, came from various sources containing geospatial information and is combined with field surveys. There were 3-18 types of land use and land cover and it did not always reflect detailed information about the research area. Meanwhile, nutrient regulation and water quality attracted the most attention for river ecosystem services. The interaction between the two variables is revealed through inferential statistics and modeling. As representations of the natural landscape, forests and grasslands have a positive and significant contribution to river ecosystem services. Therefore, knowledge of landscape and river ecosystem services is a preliminary effort to understand environmental processes in achieving sustainability, also valuable input for conservation and rehabilitation strategies in many countries. This review can be a proper reference for environmental management, especially in the landscape changes related to river ecosystem services.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
109	2	4

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INTRODUCTION

Population growth is a global phenomenon that significantly impact environmental changes. It triggers pressure on land, resource consumption, waste and garbage pollution, hydrometeorological disasters, and biodiversity (Dede *et al.,* 2019; Widiawaty *et al.,* 2020; Krsulovic *et al.*, 2022). This situation has long been predicted by Thomas Robert Malthus (1766-1834 AD), who stated that population growth would follow the geometric curve and resources referring to the arithmetic flow, it will lead to a complex environmental crisis if there are no serious efforts such as monitoring, evaluation, and planning (Lambin *et al.*, 2001; Ogundari and Otuyemi, 2019; Baud *et al.*, 2021). It is common knowledge that population growth triggers landscape transformations through land use and land cover (LULC) changes. Usually, this is dominated by converting productive agricultural lands into built-up land, while many primary and secondary forests have changed into monoculture plantations (Dede *et al.*, 2022a; Rochadi *et al.*, 2022; Suardi *et al.*, 2022; Tufa and Megent, 2022). Changes in LULC globally have caused 11 million square kilometers (km^2) of forest to be converted into anthropogenic lands (Pitman and Noblet-Ducoudre, 2012). Meanwhile, many productive agricultural lands are reduced for settlement which has another impact as observed in India, China, South America, and Southeast Asia (Nelson *et al.*, 2010). Landscape changes always have some potential impacts on the surrounding environment. On massive scales, they can affect a wider range of ecoregions across administrative borders (Clark *et al.*, 2022). The impacts can be identified with a river ecosystem service (RES) as integrated research in the environmental field. RES is used to determine the ability of natural processes and the components of rivers to provide adequate services for life needs directly or indirectly. It has attracted significant attention since the emergence of environmental degradation and reduced biodiversity in terrestrial water bodies (Camara *et al.*, 2019; Deeksha and Shukla, 2022). Research on ecosystem services is increasingly being intensified in the new millennium era. It is also an inseparable part of the Millennium Development Goals (MDGs) which are now being updated into the Sustainable Development Goals (SDGs). Efforts to determine changes in ecosystem services, including in rivers, are included in the Millennium Ecosystem Assessment (MA), officially published in 2005 by the United Nations (Reid and Mooney, 2016). RES research with various parameters has become the main concern around the world with grants reaching millions of the United States Dollar (USD) (Dufour *et al.*, 2010). This is presumably because human life and civilization are closely related to rivers that provide natural resources. A review conducted by Venkatesh *et al.* (2014) in India found that changes in the densely vegetated landscape can increase run-off and evapotranspiration as well as affect groundwater recharge to decline, but sediment levels in water bodies continued to rise. Another review by Hasan *et al.* (2020) reported that landscape changes have significant impacts on water purification processes and cultural ecosystem services from rivers. Landscape changes in mountainous regions can affect the provision of ecosystem services and their spatial variations (Pătru-Stupariu *et al.*, 2020). Additionally, they are the main trigger for changes in water balance, especially in precipitation and evaporation which then alter runoff, as well as regulating services in rivers (Ekka *et al.*, 2020). Until now, no literature review has systematically examined the relationship between landscape dynamics and RES since the MA ratification in 2005. The previous review article was too general and has not discussed the relationship between the two phenomena from a global perspective. This problem can be explored by compiling research within the systematic literature review (SLR) framework. SLR-based research provides a clear, comprehensive, and minimally biased overview to gain summarized information (Mallett *et al.*, 2012). SLR is very useful in practice for policy formulation, from the fundamental rules to technical guidelines because it contains transparent, reproducible, and precise information (Gazley, 2021; Nurbayani *et al.*, 2022). This study is very important because it summarizes previous research into a single comprehensive study, providing much convenience for other researchers in similar fields (Abdullah *et al.*, 2022; Ilmasari *et al.*, 2022; Kamyab *et al.*, 2022). This effort could understand the relationship between landscape and RES in terms of parameter formulation, data acquisition, and analytical methods for both variables from a case study perspective. Therefore, the study aims to summarize previous research about the relationship between landscape and RES in the world based on an SLR framework

published in 2005-2022. This study has been carried out in Indonesia and Malaysia in 2022.

Search strategy and eligibility criteria

This is SLR-based research conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The method is intended to create systematic reviews complemented by meta-analyses and provide a more scientific assessment of benefits (Pati and Lorusso, 2018; Basile *et al.*, 2022; Yasuda *et al.*, 2022). Using SLR, the review process will be more transparent, replicable, and scientific for theory development (Shikora and Mahoney, 2015; Franco and Groesser, 2021; Valizadeh *et al.*, 2021). The data for this review were sourced from scientific publications that have been indexed by six databases such as Scopus, Pubmed, Directory of Open Access Journals (DOAJ), Scilit, Neliti, and Garba Rujukan Digital (Garuda) as shown in Table 1. This selection is based on consideration of access and resource capabilities. Apart from Scopus, five other databases provide free services that can be freely accessed by the internet. Scopus and Scilit are managed by commercial publishers–Elsevier and Multidisciplinary Digital Publishing Institute (MDPI). This is different from Pubmed, DOAJ, Neliti, and Garuda which are provided by non-publisher institutions (Mondal and Mondal, 2020; Irawan *et al.*, 2021; Wren *et al.*, 2022). The search method to find literature referred to seven keywords such as "*landscape*", "*land use*", "*land cover*", "*ecosystem services*", "*river*", "*watershed*", and "*water*".

Selection process

Keyword-based searches across the scientific databases found a total of 82 titles but there is a need to select the titles and abstracts to ensure that there are no duplications. This step succeeded in reducing and getting 35 titles included in the 'original research article' containing case reports. Case-study articles contain the application of concepts and theories in real situations, in environmental-related investigations, usually marked by an explicit mention of the research location (Downie and Bernstein, 2019; Devasahayam, 2020; Brimicombe *et al.*, 2022). Meanwhile, original research articles usually provide more detailed information and broader exposure, have undergone through a rigorous peer-review process as well as contain novelty (Kelly *et al.*, 2014; Fernández-Sánchez and Gutiérrez-Arzaluz, 2022; Vadhera *et al.*, 2022). These articles need to be read further to obtain an overview of the research, its scope, and methodology. These works must be published by scientific journals, hence, other publication forms such as proceedings, conference presentations, technical reports, books or chapter books, and students' final projects will not be accepted for this review. Additionally, this selection did not distinguish an article from the writing systematics, because it depends on the publishers' policies.

Data extraction

A detailed and careful review of the research methodology is required to ensure the inclusion of articles. Research on landscape dynamics and ecosystem services is always related to descriptive or inferential results. This review placed more emphasis on articles that use a quantitative or mixed approach to provide more apparent results (Garcia *et al.*, 2018; Araya *et al.*, 2020; Sankofa, 2021; Buzási *et al.*, 2022). Furthermore, before considering an article eligible to be included, the entire content, from the introduction to the conclusion must be reviewed to get complete information (Ciric *et al.*, 2018; Albuquerque *et al.*, 2021; O'Brochta, 2022). The inclusion criteria included SLR-based articles showing the relationship between landscape and RES, articulated by visual and numerical evidence. Finally, this process obtained 17 articles as shown in Fig. 1. At this stage, all authors agreed on all criteria that landscape was limited to LULC.

Table 1: Detail of the databases

Database	Web address	Provider
Scopus	https://www.scopus.com/	Elsevier
Pubmed	https://pubmed.ncbi.nlm.nih.gov/	United States National Library of Medicine
DOAJ	https://doaj.org/	Infrastructure Services for Open Access
Scilit	https://www.scilit.net/advanced	MDPI
Neliti	https://www.neliti.com/	Neliti Private Limited
Garuda	https://garuda.kemdikbud.go.id/	Indonesian Ministry of Education

Quality assessment and data analysis

Eligibility assessment of the article's quality for SLR is based on the publication process to avoid non-reputable journals (Wolfram *et al.*, 2020; Chawla *et al.*, 2022). Based on the writing, the article's quality is related to the language used, pictures and tables, mentioning of scientific concepts, and references list (Alhajj, 2012; Ghazavi *et al.*, 2019; Duc *et al.*, 2020). To ensure the quality and avoid subjectivity from the authors, this effort involved three independent investigators with experience in review investigations and are concerned with the environmental research field. They came from the Indonesian State Universities with Legal Entities (PTN-BH), government research institutions, and non-profit think tanks. The investigators assessed the article as the SLR material and discussed their recommendations with the authors. A quality assessment involving external parties is an effort to reduce bias and increase objectivity rather than relying on a single point of view (Jakes *et al.*, 2021). Furthermore, extracted data from selected articles were then analyzed using content analysis to obtain in-depth written information (Khirfan *et al.*, 2020; Martinengo *et al.*, 2022; Mirzaei *et al.*, 2022). This analysis was selected because it provides flexibility for building interpretations and interconnections, emphasizing problems and identifying research gaps (Lee *et al.*, 2021; Huang *et al.*, 2022; Kim *et al.*, 2022).

Landscape assessment

Case studies to uncover the relationship between landscape and RES have spread worldwide and are not concentrated in a specific country. This situation is good because several countries are concerned about environmental sustainability related to rivers after the MA formulation (Mooney *et al.*, 2004; Ranganathan *et al.*, 2008). This review shows that countries in Asia such as China, Indonesia, Malaysia, and Sri Lanka have been interested in this topic. From North to Latin America, Brazil, Canada, Colombia, Costa Rica, Panama, and the United States have initiated this research as an effort to protect and rehabilitate terrestrial-aquatic ecosystems for areas in diverse climatic conditions. Meanwhile, similar investigations have been conducted in France and Spain, closely related to agricultural landscapes. Research from Africa specifically Congo in the Yangambi watershed was included in this review (Chishugi *et al.*, 2021). In terms of area, the median size of watersheds from previous studies was 2,617 km^2 with a range between 6.77 to 176,000 km^2. This implies that landscapes and RES research can be taken from the micro-watersheds to river basins (Poulus, 2011; Sukristiyanti

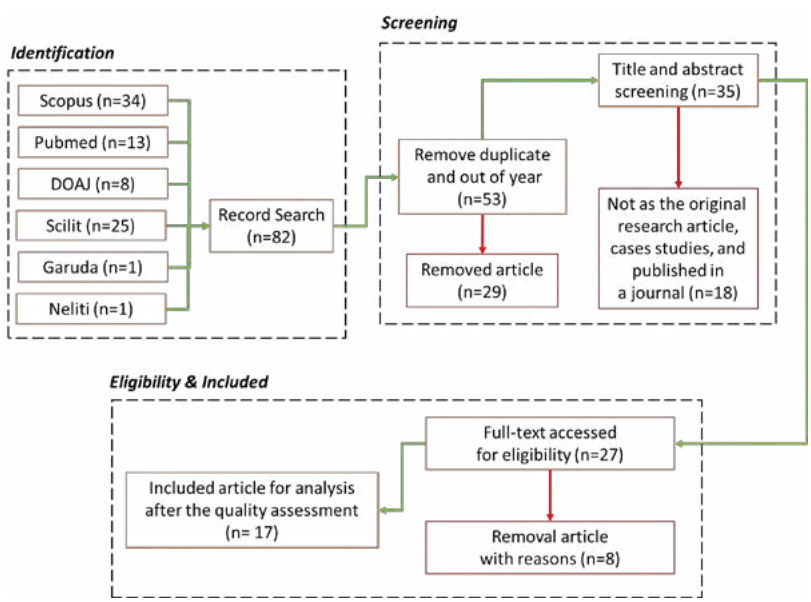

Fig. 1: Selecting processes for articles in the SLR

Table 2: Assessing landscape data for RES research

LULC type	Dataset source	Area (km^2)	Source
Agriculture, forest, cerrado (savanna woodland), regenerating vegetation, and others.	Satellite imageries (Landsat)	176,000	Stickler *et al.* (2009)
Old secondary forest, young secondary forest, and pasture.	Infrared aerial photography, Satellite Imageries (Google Earth) and ground check	35.38	Ogden *et al.* (2013)
Urban land, non-irrigated cultivated land, irrigated cultivated land, forest land, and grass and shrub land.	Analyzed-secondary vectorized data	4950	Sánchez-Canales *et al.* (2015)
Woodland, water, urban built-up area, paddy field, and dry land.	Analyzed-secondary vectorized data (Finer Resolution Observation and Monitoring of Global Land Cover)	2,617	Hao *et al.* (2015)
Forest, grasslands, urban areas, tea, and rice and vegetable cultivation areas.	Satellite imageries (Landsat), topographical maps and ground check	765	Jayawardana *et al.* (2017)
Forest, agroforestry, monoculture tree, annual crops, horticulture, rice field, settlement, shrub and grass, and cleared land.	Measured or modeled data	4,660	Van Noordwijk *et al.* (2017)
Forestry-based reclamation, covering grass, shrubs, water, developed, barren, forest, and pasture.	Satellite imageries (Landsat)	3,429	Gurung *et al.* (2018)
Agricultural, artificial, and natural area	Secondary (Corine Land Cover, ESA Copernicus)	6,775	Raitif *et al.* (2018)
Agriculture, forestry, forest, protected forest, and major freshwater systems.	Field survey	228	Hanna *et al.* (2020)
Dense forest, perturbed forest, cropland, grassland, bare soil and residential, and water bodies.	Satellite Imageries (Sentinel-2B and Google Earth)	430	Chishugi *et al.* (2021)
Forest, wetland, urban, grassland, cropland, and bareland.	Satellite imageries (Landsat) and ground check	2,274	Gao *et al.* (2021)
Native forest both old growth and secondary, agriculture, water body, and other land use.	Satellite imageries (RapidEye and Google Earth) and ground check	4,200	Hilary *et al.* (2021)
Residential area, forest, agriculture, industrial area, facilities, and businesses & services.	Satellite imageries	3401.5	Shehab *et al.* (2021)
Glaciers/permanent snow, bare rock, bare soil, stope, transportation land, construction land, river/canal, reservoir/pond, lake, wetland, dry land, paddy land, grassland, marshy, orchard/perrennial plantation, bush fallow, and broad-leaf and mixed forests.	Analyzed-secondary vectorized data (Resources and Environmental Sciences Data Center, Chinese Academy of Sciences in Beijing)	165,383	Liu *et al.* (2021)
Row crops, forest, developed, hay/pasture, water/wetland, and grassland/shrubland.	Analyzed-secondary vectorized data (US National Land Cover Dataset)	20,460	Audia *et al.* (2022)
Agricultural, including cropland, grassland, and urban.	Analyzed-secondary vectorized data (US Census Bureau)	1,345	Campbell *et al.* (2022)
Annual cropping systems, coffee plantations, pastures, abandoned shrubland, and secondary forests.	Analyzed-secondary vectorized data and ground check	125	Galindo *et al.* (2022)

et al., 2018). Differences in the size of research areas affect the landscape details to be analyzed, especially when using geospatial approaches. The details are reflected in the number of LULC types as variables for RES changes, as shown in Table 2. Three types of LULC were involved depending on the human intervention level in the environment such as Ogden *et al.* (2013); Ratif *et al.* (2018), and Campbell *et al.* (2022). These research have a study area that is significantly different in size below 50 km^2 as well as more than 1,000 km^2. Most of the landscape details (18 LULC types) are due to Liu *et al.* (2021), which explored this phenomenon in a river basin covering an area of 165,383 km^2. They used landscape data from the Chinese Academy of Sciences in Beijing.

LULC, as landscape representations that can influence RES dynamics, is generally classified into five types according to the geographic features in each research area. In landscape analysis methods, most data are based on remote sensing from satellite imagery or aerial photography. For historical data, the topographic maps can be used as a reference for landscape analysis (Jayawardana *et al.*, 2017). It is common for individuals to use analytical data provided by reputable research institutes worldwide, typically in vector format. When using raw data from remote sensing imagery (raster files), ground surveys are required to improve accuracy or guide supervised classifications (Gao *et al.*, 2021; Hilary *et al.*, 2021; Galindo *et al.*, 2022). Furthermore, secondary data analyzed in vector files might serve as a reference for performing supervised classification or visual interpretation, especially when there are limitations in the field activities (Gurung *et al.*, 2018). Details of the method and landscape data analysis are presented in Fig. 2.

Even using a multidisciplinary and interdisciplinary approach, landscape monitoring and RES assessment must keep the scientific principles from the original fields. In small watersheds, landscape analysis requires attention to the size of the research area compared to the data scale and resolution. Geospatial analysis on the landscape aspect must pay attention to the accuracy as evidenced by testing with field (ground check) or existing data that has been validated previously in various relevant and credible research (Widiawaty, 2019; Dede *et al.*, 2022b). In large watersheds, which are more than 1,000 km^2, the three LULC types are still acceptable because the data source can come from medium and low-resolution satellite imageries such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) satellites (Coe *et al.*, 2017; Daramola *et al.*, 2019). This situation can be understood because data sources are limited, also, previous access was not diverse and open. Since 2015, data processing technology based on cloud computing offers various advantages in using resources and providing open data catalogs that allow more advanced landscape

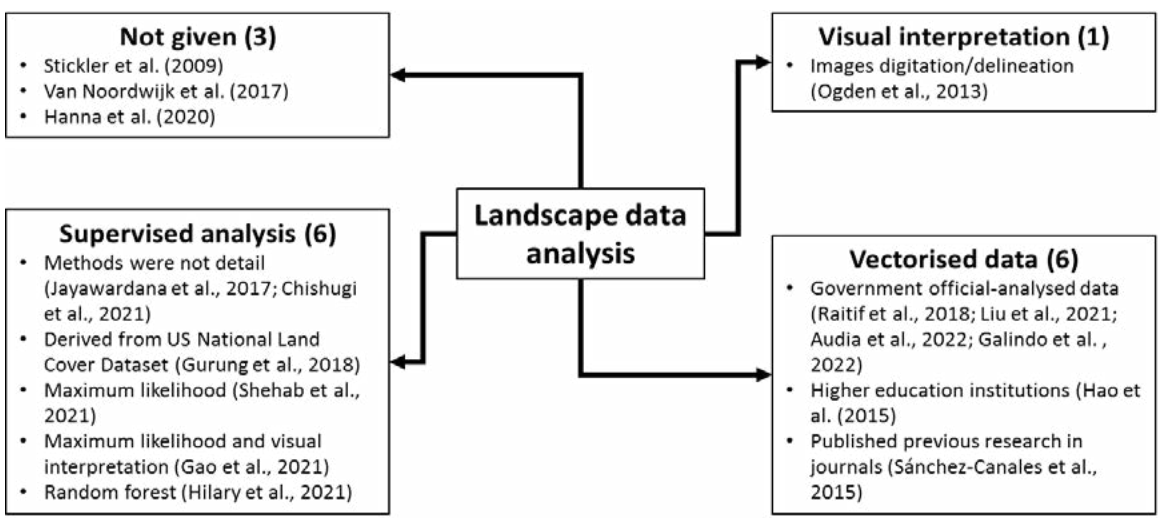

Fig. 2: Analysis method for landscape data

analysis (Dede and Widiawaty, 2020). In relatively small to medium size areas, landscapes can use other sources to obtain more detailed data, such as Landsat series, Sentinel-2 A/B, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Worldview imageries. For more detailed data, aerial vehicles are used but they have implications for the costs of procuring, storing, and processing

Table 3: RES parameter and its additional factors

Ecosystem services	Parameter	Additional factor	Author(s)
Nutrient regulation	Phosphate, nitrate, and carbon (C:N, C:P, N:P ratios)	Slope and river morphometric	Gao *et al.* (2021)
Nutrient regulation	phosphate and nitrate	Climate variation	Campbell *et al.* (2022)
Ecosystem services outcomes	Nutrient delivery ratios, sediment delivery, and carbon storage	Financial services (economic valuation)	Audia *et al.* (2022)
Flood control	Water yield	Elevation, slope, and precipitation	Gurung *et al.* (2018)
Soil retention	Sediment export		
Nutrient regulation	phosphate and nitrate		
Regulating	Flood protection, erosion regulation, nutrient regulation, and water purification	Gross domestic product	Liu *et al.* (2021)
Provisioning	Freshwater		
Cultural	Recreation and aesthetics, and intrinsic value of biodiversity		
Nutrient regulation	Nitrite, ammonia, and phosphate	Riparian forest cover (buffer width)	Hilary *et al.* (2021)
Water quality	Biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), *Escherichia coli*, sulfate, phosphate, nitrate, and ammonia	Landscape metrics	Shehab *et al.* (2021)
Water quality	Temperature, potential hydrogen (pH), conductivity, turbidity, and dissolved oxygen	River morphometric, water poverty index, and climatic aspect	Chishugi *et al.* (2021)
Water quality	Total sediment exported	climate-driven parameter and river morphometrics	Sánchez-Canales *et al.* (2015)
Water quality	Temperatures and dissolved oxygen	Surface hydrology and regional climate and carbon sequence	Stickler *et al.* (2009)
Water quality	Clean water, carbon storage, wild foods, recreation, and habitat quality	Watershed types	Hanna *et al.* (2020)
Biodiversity	Terrestrial and aquatic biodiversity		
River health	Catchment and water quality, macroinvertebrate indices and community composition	Catchment-spatial scale and seasonal conditions	Jayawardana *et al.* (2017)
Aquatic insect emergence	The presence of *Trichoptera*, *Chironomidae,* and *Ephemeroptera*	Watershed scale and site scale	Raitif *et al.* (2018)
Flood control	Measured flow persistence derived from measurements in the wettest and driest 3-month periods of the year	Rainfall, infiltration, interception, groundwater, and river morphometric	Van Noordwijk *et al.* (2017)
Hydrological control	Infiltration, runoff, and erosion rates	Rainfall, slope, and aggregate Morphology	Galindo *et al.* (2022)
Water stream flow	High and low flows	Climate, evapotranspiration, groundwater, and leaf area index	Hao *et al.* (2015)
Runoff control	Dry season river runoff, runoff efficiency, and peak storm runoff	Rainfall, catchment runoff, and evapotranspiration	Ogden *et al.* (2013)

information (Aljohani *et al.*, 2021; Gomez *et al.*, 2022; Sunardi *et al.*, 2022). Landscape needs attention to analytical methods to obtain valid and reliable LULC information. Meanwhile, the visual interpretation method promises advanced accuracy although it is time-consuming and requires the ability to explore detailed landscapes in the research area. Supervised and unsupervised classifications are certainly helpful, although they pose challenges in data quality. Ground check or comparison data is a mandatory material when choosing these methods to obtain proper quality in landscape information. Another important factor in landscape data is accuracy testing, the ability to use overall accuracy, overall kappa, producer accuracy, or other assessment (Foody, 2020; Ismail *et al.*, 2020; Ismail *et al.*, 2022). Ideally, landscape analysis uses interval data between 5-10 years thus LULC changes can be known more clearly. Researchers need to pay attention to time or seasonal aspects when using remote sensing data. This timing could affect vegetation greenness, cloud covers, and reflecting values. Without proper data preprocessing, it would influence information quality.

River ecosystem services and its relation with landscape

For many RES research, regulating services have become different individuals' primary choices. The key to understanding these services in rivers referred to nutrient regulation that analyzes various nutrient content ranging from phosphate and nitrate/nitrite (Hilary *et al.*, 2021; Campbell *et al.*, 2022). Few research also included other parameters such as carbon (Gao *et al.*, 2021; Audia *et al.*, 2022), sediment content and clean water, as well as aesthetics elements (Liu *et al.*, 2021; Karbassi and Pazoki, 2015) as presented in Table 3. The ecosystem services coupled with water quality present parameters related to physicochemical properties. However, a water quality investigation by Shehab *et al.* (2021) found other parameters including an abundance of Escherichia coli, nutrients, and ammonia. Other parameters were also discovered by Hanna *et al.* (2020), which presented information on habitat quality, foods chain, and terrestrial biodiversity. There is a growing interest in aquatic biodiversity ranging from microorganisms, benthos, and insects. In ecosystem services related to water balance, there are similarities between run-off and changes in discharge. When linked to the landscape, these parameters are initial assessments to understand flood events in the watersheds (Alivio *et al.*, 2019). Nutrient regulation focused on nitrate and phosphate are known as indicators of aquatic ecosystems' productivity and food chains. Biological, physical, and chemical parameters are crucial to understanding environmental changes that will affect water resource quality. It is related to the quality standard for usage by people with various needs. The difference in parameters can be caused by the research capabilities such as costs, human resources, instruments, and laboratories.

Perennial landscapes have been demonstrated to maintain and increase RES in nutrient regulation, runoff control, water supply, and water quality as shown in Table 4. Aside from densely-vegetated lands, grassland has a similar ability, although its impact on RES is not as strong as forest. Chishugi *et al.* (2021) found that grassland strongly affects temperature, aquatic dissolved oxygen, and pH regulation. Agricultural land and built-up areas are cultural landscapes, but the presence of crops certainly has advantages because of its ability to create an agroecosystem that enhances RES (Hao *et al.*, 2015; Ratif *et al.*, 2018). This review revealed an interesting phenomenon where riparian vegetation positively impacted water quality and temperature (Stickler *et al.* 2009). Landscape changes impact increasing air temperature which triggers the weathering processes of rock and soil as well as biogeochemical cycles in the surrounding area (Karbassi *et al.*, 2015). Landscape changes have implications for the reduced densely vegetated areas and decreased ecosystem functions for the community. Economically, this phenomenon can be detrimental to agricultural businesses, increasing electricity consumption for cooling, and also damaging goods and buildings. The loss of habitat and its biodiversity will impact people's livelihoods, thus efforts to maintain the landscape needs responsibility for all stakeholders. For RES studies, especially if researchers use the water quality parameters, they can include discussions about quality standards in each country by referring to guidelines and regulations from relevant institutions and ministries, both at the local and national levels. Meanwhile, interactions between landscapes and RES are determined by inferential statistical techniques such as regression models, analysis of variance, bivariate correlations, probability analysis,

Table 4: Significant relation of landscape and RES

Landscape type	RES Parameter	Method	Author(s)
Perennial cover	Reduced perennial covers decreased the levels of nitrate and phosphate	Mathematical modeling	Campbell *et al.* (2022)
Forest	Deforestation adversely affected water yields and nutrient levels	Multiple linear regression (MLR) and Akaike Information Criterion (AIC)	Gurung *et al.* (2018)
Grassland, cropland, forest, and wetland	Landscape changes influenced nutrient levels in river water	Multiple linear regression (MLR) and Directional index	Gao *et al.* (2021)
Landscape fragmentation	Landscape fragmentation influenced RES changes	Geographically weighted regression (GWR) and Ordinary least square (OLS) regression	Liu *et al.* (2021)
Forest	Forest was able to reduce the peak run-off by 35%	Sponge-effect hypothesis, hydrograph analysis, and probability analysis	Ogden *et al.* (2013)
Water bodies, forest	Clean-water provision, carbon storage, habitat quality, and tree diversity were significantly higher in and around streams surrounded by forest	Generalized linear models (GLMs), analysis of variance (ANOVA), Kendall rank correlations, and permutational multivariate analysis of variance (PERMANOVA)	Hanna *et al.* (2020)
Forest, degraded land	Forests are more effective in slowing water flow in the four watersheds in Southeast Asia	Pair-wise comparison test and GenRiver model.	Van Noordwijk *et al.* (2017)
Grassland, forest	Grassland has a strong influence on temperature, dissolved oxygen of water and pH. Forest is related to turbidity, conductivity, and pH properties	Analysis of variance (ANOVA), Pearson's correlation test, and simple linear regression (SLR) models	Chishugi *et al.* (2021) Karbassi and Heidari, (2015)
Agricultural, forest, and abandoned land	Forest affected hydrological services than abandoned land (42% of variance explained), especially runoff and sediment	Analysis of variance (ANOVA) with Tukey tests	Galindo *et al.* (2022)
Forest	Chemical water, including conductivity and total dissolved solids, is mostly governed by the land cover	Principal component analysis (PCA), bivariate regression analysis, and multifactorial ANOVA	Jayawardana *et al.* (2017)
Grassland	Expansion of grassland reduced annual nutrient and sediment loss. It also increased soil carbon sequestration over 10 years	Land use scenario modeling	Audia *et al.* (2022)
Riparian forest cover (buffer length)	Riparian forest cover had a more positive effect on water quality parameters than others. The greater support for influencing water quality based on its length ranged from 1000 meters > 500 meters > 100 meters (m)	Principal component analysis (PCA), Akaike Information Criterion (AIC), and R2 formulation for mixed models	Hilary *et al.* (2021)
Agricultural landscape	Agricultural landscape influenced emerging drymass of aquatic insects	linear mixed model (LMM) with a Gaussian distribution and Akaike Information Criterion (AIC)	Raitif *et al.* (2018)
Forested and cultivated non-irrigated land	Land cover management played in decreasing the sediment loads	Spearman's rank correlation, sensitivity analysis, and USLE model	Sánchez-Canales *et al.* (2015)
Urban area, agricultural lands, forest	Urban and agricultural lands were associated with water quality deterioration, and vice versa for forests	Pearson's correlation and cluster analysis	Shehab *et al.* (2021)
Riparian zone vegetation	The absence of a densely-vegetated landscape triggered higher temperatures and lower dissolved oxygen	REDD scenario model	Stickler *et al.* (2009)
Cropland and urban areas	LULC changed contributed 82-108 % to the stream flow	Z-statistics (Mann-Kendal) and sensitivity analysis	Hao *et al.* (2015)

and comparison tests. These interactions are also revealed through mathematical modeling, Akaike information criterion (AIC), principal component analysis (PCA), sensitivity analysis, REDD scenarios, permutation, and cluster analysis. According to Sánchez-Canales *et al.* (2015), a few non-parametric models can be considered an alternative to determining the interaction of these phenomena. The choice of quantitative method should be related to data characteristics. Hence, disclosing relationships between variables are accurate (Nurbayani and Dede, 2022). MA focuses on everything humans receive from ecosystems. The relationship between the two phenomena is interrelated and the assessment of ecosystem services can be addressed to the needs of each region (Carpenter *et al.*, 2009). Various RES parameters are associated with the research objectives as dependent variables. Samples for observing RES parameters are typically found in streams and water bodies, but terrestrial objects closely associated with aquatic ecosystems can also be observed. Most important in the research are samples selection and handling up to laboratory testing (Nerem, 2017). The sample selection can refer to river morphometry, landscape variations, climate, and stream pattern (Poulos, 2011). The number of samples in RES is generally not very large because it is related to the processing resources and cost.

Sampling for RES related to aquatic ecosystems such as nutrient regulation and water quality is divided into two approaches, 1) point sources; 2) non-point sources. The difference can be seen from the sampling location map when the researcher collected data on a segment (at least two points) without an inlet, this is the point sources. However, if the sampling points were spread regardless of the inlet and outlet, it means that the study referred to non-point sources. Several investigations only revealed one type of ecosystem service because other options are currently minimal. Furthermore, RES selection must have scientific justification when the indicators are quantitatively linked to the landscape or LULC. The relationship between landscape and RES can be determined using many methods such as descriptive and inferential statistics, as well as numerical/scenario modeling. The data characteristics must be appropriately understood before choosing a relational analysis while ensuring accuracy and the interpretation of results. Data types and their distribution have implications for parametric or non-parametric methods (Espejo, 2005; Riaz *et al.*, 2016; Laureano-Rosario *et al.*, 2021; Widiawaty *et al.*, 2022). For research that uses modeling and scenarios, attention must be paid to training-testing data, model testing, and sensitivity to produce robust information (Susiati *et al.*, 2022a; Susiati *et al.*, 2022b). Besides, modeling the interaction between landscape and renewable energy is neither underfitting nor overfitting, hence, a fit model must be achieved in every modeling study (Gu *et al.*, 2016; Ying, 2019; Viana *et al.*,2022), although it comes from simplifying environmental phenomena. From previous research, this review has revealed the relationship between landscape and RES can be divided into two types ie influences and correlations. The influence is characterized by using spatial/mathematical modeling, variance, comparisons, and regression analysis. This is different from correlation, it can use the Pearson, Kendal-Tau, and Spearman-Rank methods.

CONCLUSION

Landscapes and RES reviews from the elected articles indexed in six databases reveal that research on this subject spans Asia, Europe, America, and Africa. The data come from different sources which contain spatial information combined with field research activities. The research area size, usually in the form of river flow, does not always correspond to the detail of the data. The smaller area has implications for LULC types, but the involvement of RES can provide an upscaling and simplification of geospatial information. The landscape for RES research is divided into 3-18 types of LULC. This information was obtained through several analyses such as supervised, unsupervised, and vectorized-analyzed data. It is important for researchers to give more attention to spatial resolution, both using primary or secondary data for landscape analysis. Landscape classification should be more diverse for small areas, especially if the research uses high or very high-resolution spatial data sources. Meanwhile, RES data raises many parameters that are adjusted to the ecosystem service types. Previous research showed that nutrient regulation and water quality could reveal changes in RES due to landscape dynamics. RES related to water balance has been disclosed to contain parameters related to run-

off and recharge-discharge. This review revealed that natural landscapes provide more benefits to ecosystem services than anthropogenic landscapes. The presence of forests and grasslands can contribute positively to RES. Changes in forest and grassland for at least three years have significantly affected RES deterioration. However, it can also contain research on biodiversity, provisioning, and cultural services. The interaction between landscape and RES is revealed through quantitative approaches such as inferential statistics and modeling. Regression, correlation, variance analysis, probability and scenario as well as modeling are options to quantify these interactions as long as data meet the scientific criteria. Choosing an analysis model to reveal the interaction between these variables must comply with the sampling and data characteristics. Choosing the inferential statistical methods, either parametric or non-parametric should be appropriate for similar studies in the future to get more rigorous information on relationship between these variables. This review gained information about landscape and RES, which makes future research convenient, especially in selecting these parameters, data acquisition, and analytical methods. Researchers need to determine the observation interval based on dynamics in the study area and other geographical conditions. However, researchers should be emphasized the time interval for each observation, either in its season or year. Moreover, this literature review is valuable information for all stakeholders to manage landscapes through formal regulation and action. Landscape dynamics and RES are two interrelated phenomena, this study can inspire researchers, governments, communities, and environmentalists to take real action in environmental management for present and future generations based on data evidence. Landscape management needs attention to its function, even its allocation in spatial and regional terms is still important.

AUTHOR CONTRIBUTIONS

M. Dede performed the conceptualizing the draft, literature review, experimental design, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. S. Sunardi performed the conceptualizing the draft, compiled the data, and revising the final manuscript version. K.C. Lam performed the conceptualizing the draft, literature review and manuscript preparation, and review the whole manuscript. S. Withaningsih performed the literature review, prepared the manuscript text, revising the final manuscript version, remained experiments.

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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

%	Percent
AIC	Akaike Information Criterion
ANOVA	Analysis of variance
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BOD	Biochemical oxygen demand
BRIN	Badan Riset and Inovasi Nasional
C	Carbon
CIGESS	Cakrabuana Institute for Geoinformation, Environment and Social Studies
COD	Chemical oxygen demand
DOAJ	Directory of Open Access Journals
ESA	European Space Agency
Fig.	Figure
Garuda	Garba Rujukan Digital
GLMs	Generalized linear models
GWR	Geographical weighted regression
Km	Kilometer
km^2	Square kilometer
LLM	Linear mixed model
LULC	Land use and land cover
M	Meter
MA	Millennium Ecosystem Assessment
MDGs	Millennium Development Goals
MDPI	Multidisciplinary Digital Publishing Institute
MLR	Multiple linear regression
MODIS	Moderate-Resolution Imaging Spectroradiometer
N	Nitrate
OLS	Ordinary least square
P	Phosphate
PCA	Principal component analysis
PERMANOVA	Permutational multivariate analysis of variance
pH	Potential hydrogen
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PTN-BH	Perguruan Tinggi Negeri Berbadan Hukum (Indonesian State Universities with Legal Entities)
R2	r-squared or coefficient of determination
REDD	Reducing Emissions from Deforestation and Forest Degradation
RES	River ecosystem services
SDGs	Sustainable development goals
SLR	Systematic Literature Review
SLR	Simple linear regression
UPI	Universitas Pendidikan Indonesia
US	United States of America
USD	United States Dollar
USLE	Universal soil loss equation
TSS	Total suspended solids
VIIRS	Visible Infrared Imaging Radiometer Suite
WOS	Web of Science

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CONTENTS

Volume 9, Number 3, Summer 2023

(Serial # 35)

Land surface temperature changes caused by land cover/land use properties and their impact on rainfall characteristics
A. Suharyanto; A. Maulana; D. Suprayogo; Y.P. Devia; S. Kurniawan (INDONESIA) **353 - 372**

Response surface methodology and adaptive neuro-fuzzy inference system for adsorption of reactive orange 16 by hydrochar
J. Oliver Paul Nayagam; K. Prasanna (INDIA) **373 - 388**

Relationship between chlorophyll-a, sea surface temperature, and sea surface salinity
M.N. Hidayat; R. Wafdan; M. Ramli; Z.A. Muchlisin; S. Rizal (INDONESIA) **389 - 402**

Social learning activities to improve community engagement in waste management program **403 - 426**
S. Sunarti; R.S.Y. Zebua; J.H. Tjakraatmadja; A. Ghazali; B. Rahardyan; K. Koeswinarno; S. Suradi; N. Nurhayu; R.H.A. Ansyah (INDONESIA)

Toxicity of nickel oxide nanoparticle in Capoeta fusca, using bioaccumulation, depuration, and histopathological changes **427 - 444**
J. Kharkan; M.H. Sayadi; M. Hajiani; M.R. Rezaei; M. Savabieasfahani (IRAN)

Land use variation impacts on trace elements in the tissues and health risks of a commercial fish **445 - 462**
N.D. Takarina; O.M. Chuan; T.G. Pin; I. Femnisya; A. Fathinah; A.N.B. Ramadhan; R. Hermawan; A. Adiwibowo (INDONESIA)

Spatial delineation on marine environmental characteristics using fuzzy c-means clustering method **463 - 476**
E.D. Lusiana, S. Astutik, N. Nurjannah, A.B. Sambah (INDONESIA)

Performance of sewage sludge reuse in the manufacturing of fired bricks **477 - 496**
K. Moulato; M. Ammari; L. Ben Allal (MOROCCO)

Cadmium and lead uptake by wild swamp eel in the populous river **497 - 514**
N. Nurhasanah; L. Sulistyowati; E. Riani; M.R. Cordova (INDONESIA)

Modeling the tropical fish community related to land uses and environmental determinants **515 - 530**
N.D. Takarina; O.M. Chuan; M.I. Afifudin; L. Tristan; I. Arif; A. Adiwibowo (INDONESIA)

Proximate values a Proximate values and elemental analysis in wheat and soybean using inductively coupled plasma mass spectrometry **531 - 544**
G. Kowmudi; V. Rashmi; K. Anoop; N. Krishnaveni; S. Naveen (INDIA)

Sub-surface flow constructed wetland for the treatment of sewage generated in a municipal park **545 - 558**
A.M. Vazquez; A. Samudio-Oggero; H.D. Nakayama; I. Cantero-Garcia (PARAGUAY)

Sustainability index analysis of microalgae cultivated in biorefinery palm oil mill effluent **559 - 576**
A.D. Santoso; T. Handayani; D. Pinardi; K. Kusrestuwardani; N. Widyastuti; I.N. Djarot; J. Haryanti; A.I. Sitomurni; H. Apriyanto (INDONESIA)

Green transformational and transactional leadership in fostering green creativity among university students **577 - 588**
N. Saif; G.G.G. GOH; J.W. Ong; I.U. Khan (PAKISTAN/ MALAYSIA)

Urban green space during the Coronavirus disease pandemic with regard to the socioeconomic characteristics **589 - 606**
R. Setiowati; R.H. Koestoer; K. Mizuno; H.S. Hasibuan (INDONESIA/ JAPAN)

Developing a composite-based constitutive model for municipal solid waste **607 - 618**
M.R. Yousefi; A. Noorzad; M.J. Mahmoodi (IRAN)

Water security assessment framework for deltas of the transboundary river basins **619 - 636**
T.H. Truong, L.T.T. Nguyen, D.D. Nguyen, T. Pham, T.M. Vu, P.H. Nguyen, Q.T. Nguyen (VIETNAM)

Relationship between landscape and river ecosystem services **637 - 652**
M. Dede; S. Sunardi; K.C. Lam; S. Withaningsih (INDONESIA)