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ORIGINAL RESEARCH PAPER

Using a sharing-platform to prevent a new outbreak of COVID-19 pandemic in rural areas

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ABSTRACT

BACKGROUND AND OBJECTIVES: A new wave of Covid-19 pandemic has worsened the epidemiological situation in Ukraine. This caused the need to tighten quarantine measures that have been introduced since 31.08.2020. The conducted analysis showed that there are 3 groups of technologies for digital contact tracing: from maximum (25%) to minimum (20%). Objective of the study is to develop an exchange platform to track the spread of COVID-19 in rural areas.

METHODS: Factor analysis identified key factors of COVID-19 virus spread. Cluster analysis identified clusters of COVID-19 spread. Taxonomy method established the limits of using contact tracing methods. Discriminatory method makes it possible to change the applied contact tracing method.

FINDINGS: The results showed that the identified factors (medico-demographic special features of Covid-19 virus spread; rural infrastructure to counteract the infection) describe in total 83.24% of the data processed. Specified 4 clusters differ in the level of susceptibility of the population to COVID-19 and infrastructure development: from minimum (33% of the united territorial communities) to maximum- 13% of the united territorial communities. The value of the integral indicator calculated provides means for establishing the maximum (8.5) and the minimum (2) limit of changes in the method of digital contact tracing.

CONCLUSION: The developed methodology was implemented on the basis of the united territorial communities of Sumy region. Monitoring of changes in the epidemiological situation made it possible to justify the need to change the contact tracing model, which will reduce the epidemiological level in the region as a whole by 30%.

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INTRODUCTION

The latest coronavirus outbreak (Lina *et al.,* 2020) is a global problem and a serious risk for the entire world population (Alanezi *et al.,* 2020; Isaifan, 2020). In view of the unusual rate of disease spread the World Health Organization (WHO) announced the beginning of the COVID-19 pandemic on 11.03.2020 (Barbosa *et al.,* 2020). The coronavirus disease in Ukraine was recorded on March 3, 2020, when the first case in Chernovtsy region was confirmed (Sitnicki *et al.,* 2020). According to Johns Hopkins University Coronavirus Resource Center, it was confirmed that as of 02.09.2020, 25.8 million people in 188 countries were infected, 857 thousand died and 13 million recovered. (CDCP, 2020). Ukraine takes 25th place (CDCP, 2020) on the global map "COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU)" by the number of registered cases of infection with COVID-19 (129 thousand cases). The tendency of prevalence rates in Ukraine is the same as in the world: 75 thousand people recovered and 2.7 thousand died during this period, 14 thousand people have mild cases (98%), 304 (2%) are in a critical condition (CDCP, 2020). As shown in the abovementioned data the global risk of death (CFR) makes 5.71% and the recovery rate is 50% (CDCP, 2020; da Rocha *et al.,* 2020). Fear of the pandemic has led to a global panic, as a result of which all countries of the world got in an emergency situation (Teslya *et al.,* 2020). As noted by the world's leading scientists (Prem *et al.,* 2020), an irrational response to the virus has had a significant negative impact on people's lives (Dimaschko, 2020) and economy of the countries. Fortunately, all the measures that were taken at the same time around the world resulted in a positive effect (Wang *et al.,* 2020. However, there is a very high risk of a second wave of pandemic (Harko *et al.,* 2014). This is related to the fact that there is SARS-CoV-2 (Coronavirus 2 with severe acute respiratory syndrome) in some countries in the red zone of disease spread; certain restrictions on preventing the risk of infection have been prematurely cancelled; there is still no medicine or effective vaccines against the COVID-19 virus (Lee *et al.,* 2020); subsequent mutation of the virus is possible. These circumstances bring much pressure to bear upon on public health system, and there is an increasing demand for different resources; technical (Fang *et al.,* 2020) and information tools to prevent the spread of the disease (Fang *et al.,* 2020), medical personnel (Dimaschko, 2020), medication and medical facilities (Ding *et al.,* 2020), means of care for seriously ill people (Chire, 2020), etc. In order to protect the society from the virus, it is necessary to take measures related not only to physical distance (Chire, 2020, but also to use information technology to break the transmission chains and to reduce the spread of SARS-CoV-2 (Darwish *et al.,* 2020). Scientists began to develop digital tools to improve control of infectious diseases and epidemics with severe consequences even before the COVID-19 pandemic (Danquah *et al.,* 2019). However, they were mainly used to facilitate records management. The pace and scale of the COVID-19 pandemic (Davis *et al.,* 2020) required the development of fundamentally new information technologies (Reyes *et al.,* 2020) with full digitization (Teslya *et al.,* 2020) or computer-aided contact tracing. At present there are three radically different technologies and digital contact tracing platforms (Table 1). The CDCP (Center for Disease Control and Prevention) has published preliminary evaluation criteria and results of the use of contact tracing tools for active surveillance over the spread of COVID-19 (CDCP, 2020).

In general, all the technologies and platforms currently used for DCTT for active surveillance over the spread of COVID-19 can be combined into three: the first - the maximum centralized approach (example: data collection by the governments of China, South Korea (Kraemer *et al.,* 2020; Lina *et al.,* 2020; Prem *et al.,* 2020; Lee *et al.,* 2020); the second - a minimum decentralized approach (proximity tracking for privacy protection in Germany, Austria, some states of America (Teslya *et al.,* 2020; Martin *et al.,* 2020; Ding *et al.,* 2020; Means *et al.,* 2020); the third - an intermediate approach. When using the third intermediate approach, manual contact tracing is supplemented by digital data collection. There are two options for using this approach: voluntary transmission of proximity data: Denmark (Schmidt-Kraepelin *et al.,* 2020), and GPS location data to public health authorities: Singapore, Taiwan (Wang *et al.,* 2020); integration of scanned QR codes from the cell phones: Australia (Ferretti *et al.,* 2020), New Zealand (Baker *et al.,* 2020), Brazil public transport (De Biazi, 2020), face recognition cameras, credit card transactions, social networks: India (Pal *et al.,* 2020). The second option is Privacy Proximity Tracking (PPT)

using Bluetooth Low Energy (BLE) handshakes, saving information in phones as anonymous "beacons" without re-identifying users, and notifying potentially infected users of contact (Davis *et al.,* 2020). All the variety of approaches used aims to achieve a balance between technological feasibility, public health benefits, and user privacy protection. Data storage in the approaches used is possible in two

Table 1: The most common digital technologies and platforms tracking contacts for active surveillance over the spread of COVID-19

Intervention type	App name	Developer or country	Purpose, technologies used	Data storage	Participation	Government access	References
Max	WeChat / Alipay	China	Proximity - based exposure notification Bluetooth LE, GPS	Centralized	Mandatory (actually or functionally)	Data comes from government sources, location data sent to police	Kraemer *et al.*, 2020
Max	Safe Korea	Korea	Proximity - based exposure notification Bluetooth LE, GPS	Centralized	Mandatory (actually or functionally)	Data collection in the centralized database by the Ministry of Internal Affairs and Security to ensure compliance with quarantine orders and trace possible contacts	Lee *et al.,* 2020
Max	Shin Bet	Israel	Collecting metadata about contacts Sending text messages to identified individuals about the need for quarantine GPS based	Centralized	Central mandatory mass surveillance	Centralized system of forced data collection for tracking COVID-19 cases	Oliver *et al.,* 2020
Max	Pokemon Go	Taiwan	By Health Authorities; Transparent GPS based	Centralized	Central mandatory mass surveillance	Centralized system of forced data collection for tracking COVID-19 cases	Wang *et al.,* 2020
Max	Stay Home Safe	Hong Kong	Quarantine enforcement	Centralized	Central mandatory mass surveillance	The Government of the Hong Kong Special Administrative Region	Mello *et al.,* 2020
Max / Middle	ProteGO Safe	Poland	Contact tracing, medical reporting, information BLE or QR Based	Centralized / Decentralized	Voluntary app: Centralized model	Ministry of Digital Affairs of Poland: Mandatory "checks" by public health authorities, fixing a waypoint using GPS, sending "selfies" photos to the controlling agency for quarantine compliance	Woldaregay *et al.,*2020
Max / Middle	StopCovid ROBERT (ROBust and privacy-presERving proximity Tracing protocol)	France	Contact tracing, BLE or QR Based	Centralized	Voluntary app: Centralized model	Government of France, French National Assembly	Bansal *et al.,* 2020
Max/ Middle	Smittestop	Denmark	Contact tracing, BLE or QR Based	Centralized / Decentralized	Voluntary app: Centralized model	Ministry of Health and the Elderly, the Danish Agency for Patient Safety, the National Board of Health, the Danish Serum Institute, the National Board of Digitization and Netcompany	Schmidt-Kraepelin *et al.,* 2020

Continued Table1: The most common digital technologies and platforms tracking contacts for active surveillance over the spread of COVID-19

Intervention type	App name	Developer or country	Purpose, technologies used	Data storage	Participation	Government access	References
Middle ground	Blue Trace	Singapore	Digital contact tracing (DCTT) Bluetooth LE	Decentralized	Voluntary / opt-in	Mandatory government access if positive	Reyes *et al.*, 2020
Middle ground	Coronavirus Australia COVIDSafe	Australia	DCTT BLE or QR based	Centralized / Decentralized	Information, isolation registration; contact tracing	Australian Department of Health	Ferretti *et al.*, 2020;
Middle ground	NZ COVID Tracer	New Zealand	Scan QR codes to track for contract tracing purposes	Centralized / Decentralized	Voluntary app: Centralized model	The Health Ministry	Baker *et al.*, 2020
Middle ground	NHSX/Oxford; COVID Symptom Study, formerly Covid Symptom Tracker; NHS COVID-19	England	DCTT Bluetooth LE; SMS	Centralized / Decentralized	Voluntary / opt-in; self-diagnostic; multipurpose	Government maintains data, but no storage	Lewnard *et al.*, 2020
Middle ground	SwissCovid	Switzerland	DCTT Bluetooth LE, GPS DP-3T protocol	Decentralized	Voluntary / opt-in	Matching of proximity encounters happens locally on individuals' devices: Decentralized Privacy-Preserving Proximity Tracing (DP-3T) protocol or the Google-Apple Exposure Notification API	Li *et al.*, 2020
Middle ground	Aarogya Setu	India	DCTT Bluetooth LE, GPS	Centralized / Decentralized	Voluntary / opt-in	Anonymized, aggregate	Pal *et al.*, 2020;
Minimal	Care19	North Dakota USA	Proximity - based exposure notification	Centralized / Decentralized	Voluntary / opt-in	In aggregate, optional if positive	Means *et al.*, 2020
Minimal	Immuni	Italy	DCTT Bluetooth LE, GPS Proximity - based exposure notification; proximity tracing and exposure notification, optional GPS location sharing	Decentralized	Voluntary / opt-in	Ministry of Health, the Ministry for Technological Innovation and Digitalization use public infrastructures located within the national borders	Teslya *et al.*, 2020
Minimal	Stopp Corona	Austria	DCTT Bluetooth LE Proximity - based exposure notification	Decentralized	Voluntary / opt-in	Federal Ministry of Health contact tracing, medical reporting	Martin *et al.*, 2020
Minimal	ito	Germany	Proximity - based exposure notification Bluetooth LE, GPS	Decentralized	Voluntary / opt-in	None, positive results to ito server	Ding *et al.*, 2020

ways: centralized storage of impersonalized data; and decentralized storage of personally identifiable data. Ukraine is included into the red zone of COVID-19 prevalence. The degree of incidence for COVID-19 is varying in the studied Sumy region (Fig. 1).

Since the level of COVID-19 infection in rural areas of the Sumy region is varying (Fig. 1), it is necessary to justify the use of a reasonable approach to DCTT for active surveillance and to stop the spread of COVID-19 for each group of rural areas. The main

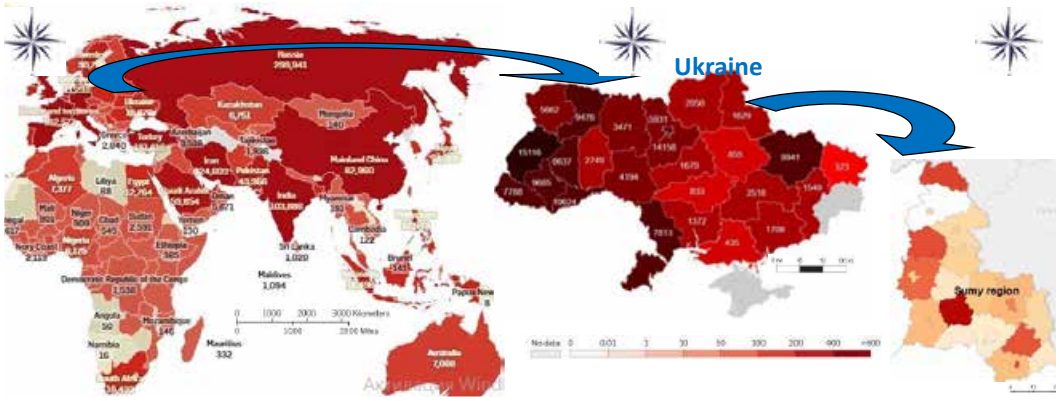


Fig. 1: COVID-19 infection level in rural areas of Sumy region, Ukraine

objective of this study is to analyze the existing DCTT methods and choose the best method to track contacts and reduce the COVID-19 infection level in rural areas of Sumy region of Ukraine. This study was conducted taking into account the data on COVID-19 infection level in 30 United Territorial Communities of rural areas of Sumy region of Ukraine for the period from April 2020 to August 2020 at runtime.

MATHERIALS AND METHODS

Materials description

The history of the epidemic started in different countries at different times. The COVID-19 spread diagram for each country with the same starting point makes it possible to compare the spread of COVID-19 in different countries (Fig. 2). The starting point for this diagram is the day when the country confirmed 100th case of infection. Trend lines represent the number of days that have passed since this event. The diagram shows the number of confirmed COVID-19 cases per 100,000 population in each country.

The first case of COVID-19 in Ukraine was registered on 03.03.2020. 198.634 total cases of COVID-19, 3.130 new cases of disease, 3.959 deaths were registered in Ukraine as of 27.09.2020. The average number of cases per 1 million population makes 4,549, the average number of deaths per 1 million population makes 91. The population of Ukraine makes 43,669,439 people. The State Commission for Technological and Environmental Safety and Emergency Situations of Ukraine decided to establish the levels of epidemic danger of COVID-19 spread by October 31, 2020. The “red” quarantine

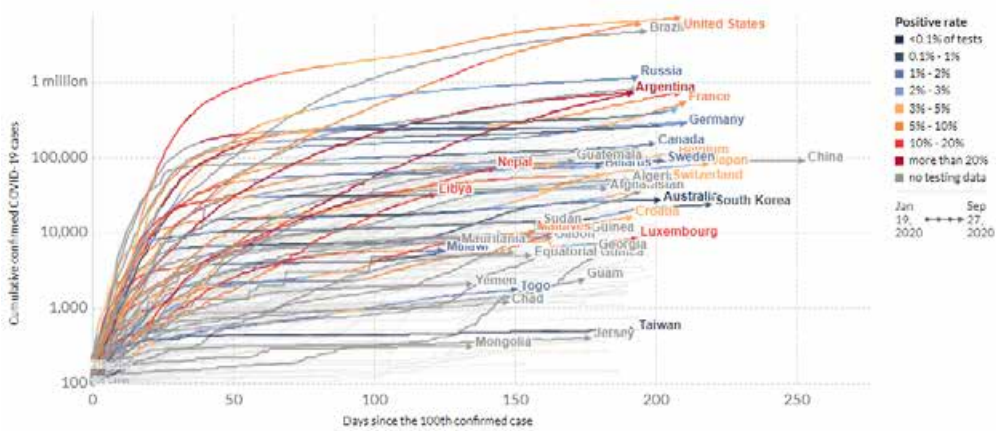


Fig. 2: Confirmed COVID-19 cases in total (CDCP, 2020)

zone included certain cities and rural areas of five Ukrainian regions: Ivano-Frankivsk, Odessa, Rivne, Ternopil and Chernivtsi. The "orange" zone included the cities of Lutsk, Uzhgorod, Lviv, Sumy, Ternopil and Kharkiv (Fig. 1). According to the data as of 28.09.20 there were only 3813 infected cases, 63 (1,7%) fatal cases, 1641 (43,0%) recovered, and 2109 (55,3%) diseased people in the studied region of Sumy. The "orange" zone of epidemic danger includes Sumy District (235 diseased, 5 deceased, 91 recovered); Konotopsky District (215 diseased, 6 deceased, 10 recovered); Bilopolsky District (117 diseased, 2 deceased, 61 recovered); Krolevetsky District (108 diseased, 2 deceased, 93 recovered). "Yellow" level was set in Shostkinsky District (106 diseased, 5 died, 55 recovered); Trostyanetsky District (90 diseased, 4 deceased, 74 recovered); Akhtyrkinsky District (98 diseased, 1 deceased, 78 recovered); Nedrigaylovsky District (80 sick, 1 died, 66 recovered); Romny District (58 diseased, 2 deceased, 33 recovered); Burynsky District (27 diseased, 2 deceased, 12 recovered); Konotopsky District (60 diseased, 3 died, 47 recovered). The rest of the districts are in the "green" zone of epidemic danger (Fig. 1). Based on the established levels of epidemic hazard of COVID-19 spread, the anti-epidemic measures on the territory of Sumy city local community were stepped up. Organizational measures were taken in Krolevetskaya, Nedrigailovskaya, Sumy and Trostyanetskaya communities to ensure that the population and business entities complied with the anti-epidemic requirements on the respective territories. The following activities are prohibited (Grossman *et al.,* 2020): activities of means of accommodation (hostels, tourist bases, etc.), except for hotels; activities of entertainment facilities, restaurants at night time; planned hospital admission; activity of gyms, fitness centers and cultural institutions; new admission to children's camps; restrictions for public events: 1 person per 20 square meters and not more than 100 people. The current epidemiological situation requires justification for differential application of DCTT models. Initial data to assess the resistance level of rural areas of Sumy region to COVID-19 are given in Table 2. The study base consisted of 13 indicators for 7 months of quarantine (March 2020 – September 2020) in Sumy region.

Initial data processing (Table 2) using the developed methodology will make it possible to make a reasonable choice of a model of COVID-19 prevalence contacts tracking for each rural area.

Methods description

Analysis of literature sources has confirmed that the use of DCTT models has proven its efficiency in preventing the spread of COVID-19. The conducted review makes it possible to assert that for rural areas with low spread of COVID-19 and mortality rates it is sufficient to use the minimum DCTT method, for areas with medium infection rate of COVID-19 - middle ground DCTT model, for areas with high infection rate of COVID-19 - maximum ground DCTT model. The first stage included the use of factor analysis. This method makes it possible to identify the most significant indicators affecting the COVID-19 infection rate and mortality in rural areas. The rows of the final table of factor analysis are equal to the number of indicators, the columns - to the number

Table 2: System of indicators affecting the resistance level of COVID-19 in rural areas of Sumy region

Indicators	Symbol
population density (number of residents per 1 sq. km)	x_1
Proportion of children under 7 years of age (% of total population)	x_2
Proportion of residents over 65 years of age (% of the total number of residents)	x_3
Proportion of youth aged 20-35 years (% of total population)	x_4
mortality rate from COVID-19 (number of deaths divided by the number of confirmed cases)	x_5
mortality per 100,000 people of local population	x_6
number of confirmed cases of COVID-19 per 100,000 of local population	x_7
number of recovered from COVID-19 per 100,000 of local population	x_8
number of educational, cultural and sports infrastructure facilities per 100,000 of local population	x_9
number of health and recreation infrastructure facilities per 100,000 people	x_{10}
proportion of enterprises operating online (% of the total number of enterprises on the territory)	x_{11}
proportion of online workers (% of the total number of local working population)	x_{12}
Number of medical personnel per 100,000 of local population	x_{13}

of factor loads of indicators. Factor loads reflect the correlation (dependence) of indicators and factors, red color shows to which factor the indicator refers, sign (+) shows direct impact, sign (-) shows negative impact. This study identified 2 factors. The first one reflects the demographic situation in the studied Sumy region, i.e. the degree of physiological susceptibility to COVID-19. The second factor reflects the infrastructural readiness of rural areas to resist infection (Lipsey *et al.,* 2000). The factor analysis was conducted by means of STATISTICA program. In general, the situation of combatting COVID-19 is described as the resistance of rural areas to the spread of COVID-19 depending on two factors: demographic situation and infrastructure development of the area using Eq. 1.

$$Cov_i = \sum_{j=1}^{N} F_j \quad (1)$$

Where, Cov_j reflects the stability of the *i*-territory; F_j- *j*-factor (demographic / infrastructural aspect of susceptibility / resistance to COVID-19); *N* - number of factors identified. The value of each factor (susceptibility / resistance to COVID-19) is determined using Eq. 2.

$$F_j = \frac{1}{Expl.F_j} \times \sum a_{ij} \times X_{ij} \quad (2)$$

Where, $Expl.F_j$ is the factor load *j* - the susceptibility / resistance aspect of COVID-19; a_{ij} is the value of the indicator X_{ij}; X_{ij} is the *ij* indicator.

Cluster analysis of K-average was used at the second stage to justify the division of rural areas into groups by the level of prevalence and susceptibility of population to COVID-19.

The methodology of using K-average cluster analysis is as follows:

- Prior conversion of all indicators to a dimensionless form using Eq. 3.

$$z_{ij} = \frac{x_{ij} - \overline{x}_j}{S_j} \quad (3)$$

Where, x_{ij} is the *j*-th COVID-19 spread indicator of the *i*-th rural area; x_j is the average of this indicator for all rural areas; S_j is the standard deviation of this indicator for all rural areas.

- Minimizing the standard deviation of all indicators from the center of the identified clusters using Eq. 4 (Lipsey *et al.,* 2000).

$$min \left[\sum_{i=1}^{k} \sum x(j) \in S_i \left\| x^{(j)} - \mu \right\|^2 \right] \quad (4)$$

где $x^{(j)} \in R^n$; $\mu_i \in R^n$; μ_i – cluster centroid R_i.

- Determination of the R_i cluster centroid (center) by maximizing the distances between clusters and minimizing the standard deviation of indicators from the cluster centroid. Calculation of the centroid of each R_i cluster using Eq. 5.

$$\mu_i = \frac{1}{S_i} \sum_{x^{(j)} \in S_i} x^i \quad (5)$$

- Completion of recalculation when μ_i values do not change, using Eq. 6.

$$\mu_i^{step\ t} = \mu_i^{step\ t+1} \quad (6)$$

Where, *step t* is the previous iteration, *step t+1* is the current iteration.

The method of taxonomy was used at the third stage. This method makes it possible to determine the boundary value of COVID-19 infection level for each of the clusters as an integral indicator. The stages of taxonomy:

- Matrix formation of significant indicators identified at the first stage of factor analysis (highlighted in red in the STATISTICA listing). The initial matrix has the following form using Eq. 7.

$$X = \begin{pmatrix} x_{11}x_{12}...x_{1n} \\ x_{21}x_{22}...x_{2n} \\ ..... \\ x_{m1}x_{m2}...x_{mn} \end{pmatrix} \quad (7)$$

- Matrix transformation (7) to a dimensionless standardized form and matrix standard formation, Where, 0 is the best value in columns using Eq. 8.

$$x^0 = [x_1^0, x_2^0, ... x_n^0] \quad (8)$$

- Determination of the multidimensional Euclidean distance from the matrix standard using Eq. 9.

$$L_i = [\sum_{i=1}^{n} (x_i - x_i^0)^2]^{1/2} \quad (9)$$

- Determination of the average Euclidean distance

from all objects to the standard using Eq. 10.

$$\overline{L} = \frac{1}{N} \times \sum_{i=1}^{N} L_i \quad (10)$$

- Determination of the standard deviation of multi-dimensional distances using Eq. 11.

$$\sigma = \frac{1}{N} \left[\sum_{i=1}^{N} \left(L_i - \overline{L} \right)^2 \right]^{1/2} \quad (11)$$

- Calculation of the taxonomy indicator, which characterizes the resistance level of rural area COVID-19 using Eq. 12.

$$\eta_i = 1 \quad \frac{L_i}{\overline{L} + 2\sigma} \quad (12)$$

The obtained value of taxonomy indicator is interpreted as follows: the stronger is the resistance level of rural area to COVID-19, the closer is its value to 10.

The resistance level of rural area to COVID-19 was presented in the form of dendogram (modification of cluster analysis) by means of STATISTICA program. The fourth stage provided the use of discriminant analysis, which makes it possible to recognize objects to decide which indicators divide (i.e. "discriminate") data sets (so-called "groups"). The discriminant analysis is based on the assumption that the descriptions of objects (rural areas) of each R_i cluster represent the implementation of a multidimensional random value distributed according to the normal law *Nm(μk;Σk)* with average μk and covariance matrix using Eq. 13.

$$C_k = 1/(n_k - 1) \sum (x_{ik} - \mu_k)^T (x_{ik} - \mu_k) \quad (13)$$

Where, the index m indicates the dimension of the feature space.

Discriminatory analysis is used in this case to monitor the need to correct the applied DCTT model. That is, whether the studied rural area remained in the same cluster or whether the data on COVID-19 resistance have changed. For this purpose, linear functions to identify to which cluster the rural area is referred are established based on the following indicators: confusion matrix in the training sample and in the cross-check, identification errors and mean square distance between the centroids of two clusters. The calculated maximum value of one of two identification functions indicates that the rural area under study is included to one of the clusters and if necessary is subject to correction used by the DCTT model.

RESULTS AND DISCUSSION

The first stage included factor analysis which was conducted to identify indicators that have an impact on the rate of COVID-19 spread and the possibility of limiting the spread of COVID-19 virus (Table 3).

Table 3: Results of factor analysis. Identification of COVID-19 virus restriction indicators (STATISTICA 10 listing)

Variable	Factor Loadings (Unrotated) (data) Extraction: Principal components (Marked loadings are > 0.700000)	
	Factor 1	Factor 2
x_1	-0.790815	-0.495010
x_2	0.745745	-0.272548
x_3	-0.753503	-0.338784
x_4	0.986729	-0.368339
x_5	-0.275268	-0.028653
x_6	-0.518377	0.016648
x_7	-0.201241	0.013647
x_8	-0.072538	0.609842
x_9	-0.272548	-0.863570
x_{10}	-0.230653	0.758107
x_{11}	-0.028653	0.863570
x_{12}	0.016648	0.916809
x_{13}	-0.595590	0.753435
Expl.Var	4.062440	2.858818
Prp.Totl	0.512495	0.319909

The first factor included 8 indicators (Table 3): population density (number of residents per 1 sq. m.). km); the proportion of children under 7 years of age (% of total population); the proportion of residents over 65 years of age (% of total population); the proportion of youth aged 20-35 years of age (% of total population); COVID-19 mortality rate (number of deaths divided by number of confirmed cases); mortality rate per 100,000 people of local population; the number of confirmed COVID-19 cases per 100,000 people of local population; and the number of recovering COVID-19 cases per 100,000 people. The second factor included the rest 5 indicators: the number of educational, cultural, and sports infrastructure facilities per 100,000 people of local population; the number of health and recreation facilities per 100,000 people of local population; the proportion of enterprises working online (% of the total number of enterprises on the territory); the proportion of population working online (% of the total number of population working online); the number of medical personnel per 100,000 people on the territory. The results of the conducted factor analysis showed that the specific features of spread and limitation of COVID-19 epidemic in rural areas of Sumy region are fully characterized by two factors obtained. This is quite enough to justify the choice of DCTT model for each rural area. The first factor can be characterized as medical-demographic features of COVID-19 virus spread. It describes 51.25% of the dispersion and has the greatest impact on the epidemiological situation in rural areas. The second factor describes 31.99% of the dispersion. It characterizes the infrastructural condition of rural areas of the given territory, and socio-cultural diversification of the territory has a negative impact on limiting the spread of COVID-19 (because of the concentration of people at a single location). Other indicators of the second factor have a positive impact on limiting the spread of COVID-19 (due to the possibility of organizing social distance or providing medical care). According to Table 3, the first factor's impact on limiting COVID-19 spread is described in Eq. 14.

$$F_1=1/4.062440 \cdot (-0.790815\, x_1 + 0.745745\, x_2 - 0.753503\, x_3 + 0.986729\, x_4 - 0.275268\, x_5 - 0.518377\, x_6 - 0.201241\, x_7 - 0.072538\, x_8) \quad (14)$$

The value of the impact of the second factor on the possibility of limiting the spread of COVID-19 is determined by Eq. 15.

$$F_2=1/2.858818 \cdot (-0.863570\, x_9 + 0.758107\, x_{10} + 0.863570\, x_{11} + 0.916809\, x_{12} + 0.753435\, x_{13}) \quad (15)$$

Thus, the obtained model reflects completely the level of population's susceptibility to COVID -19 in the studied region according to two factors, the first one reflects medical-demographic peculiarities of COVID -19 virus spread in the given area, the second one represents infrastructural limitations of COVID -19 spread K-average cluster analysis was used at the second stage to justify the division of rural areas into groups according to the level of prevalence and susceptibility of population to COVID-19. The diagram of K-average is shown in Fig. 3.

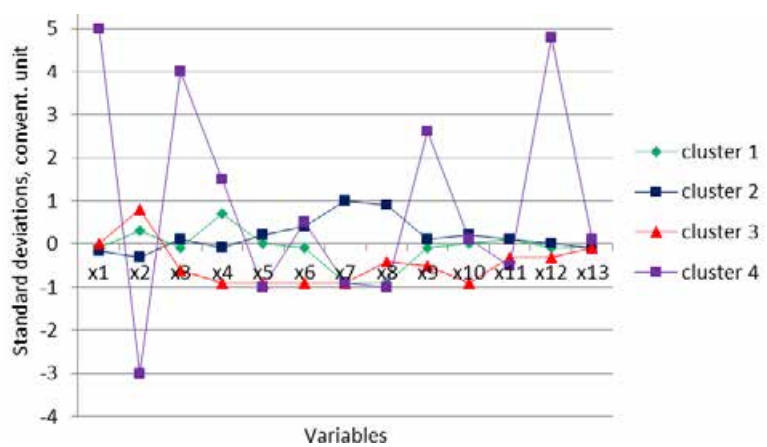


Fig. 3: Diagram of average values of indicators for the prevalence rates and susceptibility level of population to COVID-19 in rural areas of Sumy region

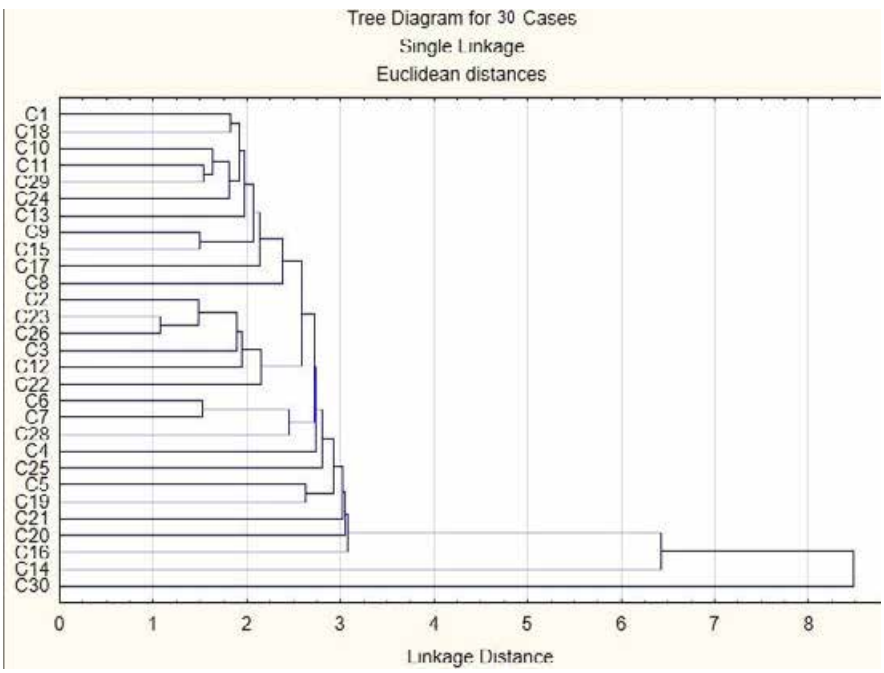
Fig. 3 shows that in accordance with the prevalence rates and susceptibility level of population to COVID-19 all the rural areas of Sumy region are divided into four clusters. The number and composition of united territorial communities (UTC), which are part of the obtained clusters, is presented in Table 4.

As the data in Table 4 show according to the identification feature: "UTC resistance level / susceptibility of population to COVID-19": cluster 1 includes UTC, where there is a low level of susceptibility of population to COVID-19 due to the small number of categories with the increased risk of infection (elderly people, children, chronic patients with compromised immune system), middle adulthood and young population prevail. Besides, there is a low level of infrastructure development, i.e., few enterprises providing services to the population (cafes, restaurants, entertainment facilities). Comparison of the first cluster identified by the model used in this study in real time mode confirms the fact that on the territory of UTC of the first cluster (Andriyashivska UTC, Bochechkivska UTC, Vilshanska UTC, Druzhbivska UTC, Dubovyazivska UTC, Kyrykivska UTC, Krasnopilska UTC, Mykolayivska (Bilopil district) UTC, Stepanovskaya UTC, Shalyhynska UTC) from the total population in Andriyashivska UTC (4,000 people - minimum) to 7.3 thousand people in Stepanovskaya UTC (maximum) - the proportion of the population aged 25 to 45 years makes 52%. Furthermore, the number of infrastructure entertainment facilities ranges from 5 facilities in Andriyashivska UTC (1.25 facilities per 1 thousand population) to 9 facilities in Stepanovskaya UTC (1.23 facilities per 1 thousand population). UTC, which were included in cluster 2, also have poorly developed infrastructure, but they

Table 4: Cluster analysis results. Determination of UTC cluster composition in Sumy region of COVID-19 virus spread (STATISTICA 10 listing)

United territorial communities (UTC) of Sumy Region	Cluster/ quantity UTC	Identification of susceptibility and resistance level of local population to COVID-19
Andriyashivska UTC Bochechkivska UTC Vilshanska UTC Druzhbivska UTC Dubovyazivska UTC Kyrykivska UTC Krasnopilska UTC Mykolayivska (Bilopil district) UTC Stepanovskaya UTC Shalyhynska UTC	1 /10	Low susceptibility of population to COVID-19 Low level of infrastructure development
Bilopilska UTC Berezivska UTC Boromlyanska UTC Znob-Novgorod UTC Mykolayivska UTC Myropilska UTC Nyzhnosyrovatska UTC Novoslobodskaya UTC Khotyn UTC	2 /9	Average susceptibility of population to COVID-19 Low level of infrastructure development
Burynska UTC Verkhnosyrovatska UTC Grunska UTC Korovynska UTC Chupakhivska UTC Shostkinskaya UTC Chernechchynska UTC	3/7	Average susceptibility of population to COVID-19 Average level of infrastructure development
Krolevets UTC Nedrigailivska UTC Trostyanetska UTC Sumy UTC	4/4	High level of susceptibility of population to COVID-19 High level of infrastructure development

have a higher level of perception of COVID-19, as the number of elderly people is higher in this area. Besides, the actual data collected from the place of research practice confirms the fact that on the territory of UTC of the second cluster (Bilopilska UTC, Berezivska UTC, Boromlyanska UTC, Znob-Novgorod UTC, Mykolayivska UTC, Myropilska UTC, Nyzhnosyrovatska UTC, Novoslobodskaya UTC, Khotyn UTC) from the total population (from 3 to 3). 6 thousand people in Bilopilska UTC (minimum) to 5.5 thousand people in Khotyn UTC (maximum) - the proportion of the population over 60 years is on average 58%. At the same time, there are also few infrastructure facilities of entertainment nature: from 3 facilities in Bilopilska UTC (0.83 objects per 1 thousand population) to 4 facilities in Khotyn UTC (0.72 objects per 1 thousand population). Cluster 3 is characterized by an average level of susceptibility of the population to COVID-19 (middle age population prevails), an average level of infrastructure development (more enterprises and residents working online in comparison with the first and second clusters). The actual data collected from the place of research practice confirms as well the fact that on the territory of UTC of the third cluster (Burynska UTC, Verkhnosyrovatska UTC, Grunska UTC, Korovynska UTC, Chupakhivska UTC, Shostkinskaya UTC, Chernechchynska UTC) the population aged 45-60 years (from 10 years) prevails. 2 thousand people in Chernechchynska UTC (minimum) to 14 thousand people in Burynska UTC (maximum) - the proportion of the population aged 45-60 years makes 47%. At the same time, the number of infrastructure entertainment facilities is as follows: 12 facilities in Burynska UTC (0.86 objects per 1 thousand population) to 14 facilities in Burynska UTC (1 object per 1 thousand population), the proportion of population working online is on average 33%. Cluster 4 is characterized by a high level of susceptibility of population to COVID-19 and a high level of infrastructure development. The actual



Symbols of united territorial communities: Krolevets: Andriyashivska UTC C_1; Bilopilska UTC C_2; Berezivska UTC C_3; Boromlyanska UTC C_4; Bochechkivska UTC C_5; Burynska UTC C_6; Verkhnosyrovatska UTC C_7; Vilshanska UTC C_8; Grunska UTC C_9; Druzhbivska UTC C_10; Dubovyazivska UTC C_11; Kyrykivska UTC C_12; Korovynska UTC C_13; Trostyanetska UTC C_14; Mykolayivska (Bilopil district) UTC C_15; Krolevets UTC C_16; Mykolayivska C_17; Myropilska UTC C_18; Nyzhnosyrovatska UTC C_19; Nedrigailivska UTC C_20; Novoslobodskaya UTC C_21; Stepanovskaya UTC C_22; Krasnopilska UTC C_23; Khotyn UTC C_24; Chupakhivska UTC C25; Shalyhynska UTC C_26; Shostkinskaya UTC C_27; Znob-Novgorod UTC C_28; Chernechchynska UTC C_29; Sumy UTC C_30.
9.

Fig. 4: Integral indicator of resistance and prevalence rates of COVID-19 of the united territorial communities of Sumy region

Table 5: Results of discriminant analysis. Monitoring of changes in the epidemiological situation COVID-19 in rural areas of Sumy region (STATISTICA 10 listing)

Discriminatory function of changing the epidemiological situation of COVID-19 of the *i*-th cluster	DCTT model usage condition for UTC *i*-th cluster residents	Suggested DCTT methods of COVID-19 new pandemic outbreak prevention platform
Int_1= 0.262 - 0.81x_1 + 0.74x_2 - 0.75x_3 + 0.98x_4 - 0.27x_5 -0.51x_6 - 0.21x_7 - 0.07x_8 - 0.86x_9 + 0.75x_{10} + 0.86x_{11} + 0.91x_{12} + 0.75x_{13}	Int_1 = max	For the residents of UTC *i*-th cluster it is suggested using the minimum methods of contact tracing: manual notification of the case of COVID-19 by phone, sms-notifications.
Int_2= 0.321 - 0.73x_1 + 0.83x_2 - 0.62x_3 + 0.99x_4 - 0.19x_5 -0.42x_6 - 0.19x_7 - 0.06x_8 - 0.77x_9 + 0.82x_{10} + 0.83x_{11} + 0.92x_{12} + 0.79x_{13}	Int_2 = max	For the *i*-th cluster it is suggested using medium-minimal methods of tracking contacts: manual notification of COVID-19 cases by phone, sms-notifications; voluntary service of people who had contact with the carrier COVID-19.
Int_3= 0.428 - 0.69x_1 + 0.86x_2 - 0.59x_3 + 1.02x_4 - 0.17x_5 -0.40x_6 - 0.17x_7 - 0.05x_8 - 0.75x_9 + 0.88x_{10} + 0.88x_{11} + 0.93x_{12} + 0.81x_{13}	Int_3 = max	For the *i*-th cluster it is suggested using the average methods of tracking contacts: automatic notification of COVID-19 cases, verification of quarantine conditions by public health authorities, fixing the waypoint using GPS, sending "selfies" photos to the controlling agency for quarantine compliance.
Int_4= 0.555 - 0.59x_1 + 0.88x_2 - 0.49x_3 + 1.03x_4 - 0.13x_5 -0.37x_6 - 0.13x_7 - 0.03x_8 - 0.66x_9 + 0.98x_{10} + 0.98x_{11} + 0.99x_{12} + 0.88x_{13}	Int_4 = max	For the residents of UTC *i*-th cluster it is suggested using the most stringent methods of tracking contacts: automatic notification of COVID-19 cases, centralization of information in the UTC administration, public health authorities, forced examination of people who had contact with the carrier COVID-19.

data collected from the place of research practice confirms as well the fact that on the territory of UTC of the fourth cluster (Krolevets UTC, Nedrigailivska UTC, Trostyanetska UTC, Sumy UTC) the population aged 45-60 years prevails (from 8.5 thousand people in Nedrigailivska UTC (minimum) to 78.8 thousand people in Sumy UTC (maximum) - the proportion of population aged 45-60 years makes 44%. At the same time, the number of infrastructure entertainment facilities is as follows: 12 facilities in Nedrigailivska UTC (0.86 facilities per 1 thousand population) up to 54 facilities in Sumy UTC (0.7 facilities per 1 thousand population), the proportion of population working in the remote mode is on average 13%. This situation is explained by the fact that the fourth cluster includes UTC, located near large cities, transport highways, highly developed infrastructure, a large number of critical population groups (Kolodiziev *et al.*, 2018). Previous studies have shown that refugees living in rural areas near large cities have an additional social burden (Shcherbak *et al.*, 2020). All these factors certify that these four clusters require applying different models of tracking contacts with COVID-19 patients. In other words, it is necessary to offer a comprehensive platform to prevent a new outbreak of COVID-19 pandemic with differentiation of COVID-19 contact tracing models by different UTC clusters. Integral COVID-19 prevalence rate indicators for each of the clusters were calculated at the third stage by means of taxonomy using equations 7 - 12. The value of the integral COVID-19 prevalence rate indicator shows the boundary where one contact tracing model is transformed into another model. COVID prevalence rate indicator of different UTCs was presented in the form of a dendogram (Fig. 4) by means of STATISTICA software.

Fig. 4 show that the closer the COVID-19 integral value is to 10, the more stringent measures to track contacts with COVID-19 carriers are required. The last stage included the use of discriminant analysis. It was used to monitor the dynamics of the epidemiological situation in the identified clusters. If the situation worsens or improves, it is necessary to change the means of tracking contacts with COVID-19 carriers used. The result of the conducted discriminant analysis is given in Table 5.

The use of the suggested discrete method to monitor the situation of spread of COVID-19 makes it possible to: identify possible deterioration (improvement) of the situation, quickly and efficiently propose changes in the methods of tracking contacts COVID-19 and appropriate quarantine measures.

It is suggested to use discriminant analysis in case of need to choose and modify the contact tracing model. It is suggested to monitor the status COVID-19 spread on a weekly basis using the indicators of the

developed model. New actual data are substituted in 4 discriminant equations. Each equation corresponds to one of the four contact tracing methods. Maximum value of the integral indicator of the discriminant equation shows the need for an appropriate contact tracing method. Testing of the suggested model has proved that timely change of the used COVID-19 contact tracing method will reduce the epidemiological level by 30% as a whole.

CONCLUSION

The conducted analysis of existing methods of response to COVID-19 pandemic has shown that traditional methods need to be complemented by digital technologies that facilitate epidemiological surveillance of public health and tracking of contacts. Technologies and platforms for digital contact tracing can be roughly categorized into three groups: the maximum approach (central government data collection), applied in 25% of countries; the minimum approach (decentralized confidentiality and contact notification), applied in 20% of countries; various options for the intermediate approach (supplementing manual contact tracing with digital data collection that can be transferred to public health authorities), applied in most countries that is 65%. The analysis confirms that there is no one-size-fits-all approach to DCTT. Technology design should not be static, but it should be able to develop depending on local conditions, new data and changing preferences and priorities. This prerequisite was the basis for the sharing-platform developed to track over the spread and resistance of COVID-19 in rural areas. The proposed methodology was tested in rural areas of Sumy region. The use of the suggested platform is based on the methodology consisting of four stages. The first stage provides identification of the most significant indicators affecting the epidemiological situation by means of factor analysis. These indicators are grouped into 2 factors. The first factor reflects the medical-demographic features of the COVID-19 virus spread, and reasons 51.25% of the dispersion. The second factor reflects the infrastructural readiness of rural areas to resist the infection, reasons 31.99% of the dispersion. At the second stage, 4 clusters were identified by the level of susceptibility of the population and the level of resistance of UTC to COVID-19 by means of K-average cluster analysis. The identified clusters reflect the current epidemiological situation in rural areas of Sumy region. In 33% of UTC of the first cluster there is a low level of susceptibility of population to COVID-19 and low level of infrastructure development. In 30% of UTC of the second cluster there is an average level of susceptibility of population to COVID-19 and low level of infrastructure development. In 24% of UTC of the third cluster there is an average level of susceptibility of population to COVID-19 and a low level of infrastructure development. In 13% of UTC of the first cluster there is a high level of susceptibility of population to COVID-19 and a high level of infrastructure development. In the third stage, the boundary value of COVID-19 prevalence rates for each cluster was determined by the taxonomy method as an integral indicator. The calculations showed that the maximum value of the integral indicator is observed in Sumy UTC (8.5), the minimum is found in Andriyashivska UTC (2). The fourth stage provides using discriminant analysis, by means of which we monitor changes in the epidemiological situation of COVID-19 in rural areas of Sumy region and, if necessary, correct the applied DCTT model. The maximum value of discriminant function shows to which cluster UTC is referred and which tracking system of contacts and quarantine measures should be applied/changed. Interactive use of the sharing platform makes it possible to improve the system of tracking the spread and resistance of COVID-19 in rural areas of Sumy region by 30%, which improves the epidemiological situation in the region as a whole.

AUTHOR CONTRIBUTIONS

V. Shcherbak substantiated the study methodology, validation, conceptualization, I. Gryshchenko supervised the interaction with the administration of rural areas of Sumy region, L. Ganushchak-Yefimenko collected and analyzed literature, O. Nifatova collected data on epidemiological situation in Sumy region, state of infrastructure on the territory of the united territorial communities, V. Tkachuk wrote the initial project plan, T. Kostiuk provided software for information processing, V. Hotra calculated models and presented a graphical presentation of the material.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

%	Percentage
Aarogya Setu	Special electronic contact tracking application in India
AIDS	Acquired immune deficiency syndrome
BLE	Bluetooth (wireless data transfer protocol) with low power consumption
Bluetooth LE	Low power wireless data transfer protocol
BlueTrace	Special electronic contact tracking application in Singapore
Care19	Special electronic contact tracking application in New Dakota USA
CDCP	Center for Disease Control and Prevention
CFR	Global risk of death
Coronavirus_ Australia	Dedicated electronic contact tracking application in Australia
COVIDSafe	
COVID-19	COronaVIrus Disease 2019, coronavirus infection 2019-nCoV
CSSE	Center for Systems Science and Engineering
DCTT	Digital contact tracing technologies
DP-3T protocol	Bluetooth contact chain tracking protocol to prevent coronavirus proliferation SARS-CoV-2
Eq.	Formula of calculation
Expl.Var	Explanatory Variable
Fig.	Figures
GPS	System of global positioning
JHU	Johns Hopkins University
Immuni	Special electronic contact tracking application in Italy
ito	Special electronic contact tracing application in Germany
km	Kilometer
NHSX/Oxford; COVID Symptom Study, formerly Covid Symptom Tracker; NHSCOVID-19	Special electronic contact tracing application in Great Britain
NZ_COVID_Tracer	Special electronic contact tracking application in New Zealand
Pokemon Go	Special electronic application for centralized contact tracking in Taiwan
PPT	Privacy Proximity Tracking
ProteGOSafe	Special electronic contact tracking application in Poland
Prp.Totl	Percentage of the total variance explained
QR	Easy recognition quick response code
ROBERT	Special electronic contact tracing application in France
Safe Korea	Special electronic application for centralized contact tracing in Korea
SARS-CoV-2	Coronavirus 2 with severe acute respiratory syndrome
Shin Bet	Special electronic application for centralized contact tracing in Israel
Smittestop	Dedicated electronic contact tracking application in Denmark
SMS	“Short Message Service” - technology for receiving and sending short text messages using a cell phone
STATSTICA	Statistical analysis software package
Stay_Home_Safe	Dedicated electronic application for centralized contact tracing in Hong Kong
StopCovid	Special electronic contact tracing application in France
Stopp_Corona	Special electronic contact tracing application in Austria
SwissCovid	Special electronic contact tracing application in Switzerland
TC	Territorial Community
UAH	hryvnya
UTC	United Territorial Community
Var	Variable

WeChat/Alipay	Special electronic application for centralized contact tracing in China
WHO	World Health Organization

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ORIGINAL RESEARCH PAPER

Prioritization of the effective factors in reducing energy consumption in a residential building using computer simulation

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ABSTRACT

BACKGROUND AND OBJECTIVES: According to the latest energy balance sheets, the average energy consumption in the residential sector of Iran is about 41% of the total energy consumption in the country. Increasing the energy efficiency of buildings can decrease the annual energy consumption in the residential sector and, thereby, the energy costs of families. The objectives of this study were to evaluate and prioritize the effective factors in reducing the energy consumption in residential buildings in the north of Iran using the climatic conditions analysis.

METHODS: In the first step, the amount of energy consumption in the cooling and heating section was estimated in the base conditions, and in the next step, the amount of energy consumption was calculated. The obtained results were compared with each other with the help of optimization strategies for energy consumption using the Design Builder software. Finally, a set of effective factors were determined to be involved in decreasing the energy consumption.

FINDINGS: The results showed that application of the LED lamps instead of the conventional fluorescent lamps could decrease the energy consumption by 980.4 kWh. Moreover, changing the materials of the walls and ceiling, using the polyurethane foam insulation with the thickness of 20 mm, and using the double-glazed UPVC windows reduced the energy consumption by 770 kWh. Energy reduction of about 101.5 kWh was also obtained after external movable awning and internal blind.

CONCLUSION: The most commonly used materials were analyzed by the Design Builder software. The analysis was done by integrating building architecture engineering (the best form of orientation and facade) based on the reasonable costs of consuming common materials in the area. The obtained results can be used for both evaluating the energy efficiency in residential buildings and producing a comfortable living environment in a moderate and humid climate.

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INTRODUCTION

According to the latest energy balance sheets, the average energy consumption in the residential sector of Iran is about 41% of the total energy consumption in the country (Energy Balance, 2017; Amani and Kiaee, 2020). This rate is more than the average energy consumption in the residential sector in the world and almost ten times greater than the average energy consumption in the advanced countries such as the United States and some European countries. Considering the built environments, residential buildings are among the main generators of environmental externalities (Ingrao *et al.,* 2018). From the total amount of energy consumed, 71% is used in household and heating sections, 22% is used in water circulation and 7% is used for general domestic purposes. Increasing the energy efficiency in the buildings can decrease the annual energy consumption in the residential sector and, thereby, the energy costs of families (Stephens, 2011). Common approaches for supplying sustainable energy are oriented towards providing the energy required in the buildings by decreasing the amount of used fossil fuels and increasing the amount of used renewable energies. The past architecture in Iran, relying on knowledge, experiences and precious patterns, has represented intelligent strategies in this field. This architecture has managed to establish a specific harmony with the environment and, by following it, has been successful in utilizing the forces of nature or confronting the difficult climate conditions (Yazdan Panah and Heidari, 2015). However, the point which cannot be ignored is that 95% of these buildings have a high energy consumption, so that 43% of the total social energy consumption in Iran belongs to energy consumption of the buildings. Therefore, supporting ecological energy saving and developing green buildings have become important activities in Iran (Amani, 2018). Table 1 shows an overall review of the previous studies on building energy efficiency rendered by energy simulation software. These studies have been extracted from popular databases, including Science Direct, Emerald, ASCE, and Taylor and Francis. The covered issues are the buildings' energy saving and efficiency evaluated by the Energy Plus simulation software.

Table 1 indicates that no study has evaluated the building energy efficiency by prioritization of effective factors in residential buildings based on the Design Builder simulation software. In this study, for the first time, the most commonly used materials are analyzed by the powerful Design Builder software. This was done by integrating building architecture engineering (the best form of orientation and facade) for the first time. The main objective of this study is to analyze the impact of the factors involved in reducing energy consumption in buildings using the climatic conditions analysis in Namakabroud, Chalous. For this purpose, the obtained climate data and basic building information were transferred to the software and energy outputs were monitored during one year. In the next step, after changing the design of the building and analyzing it by the software, the optimum conditions of energy consumption was achieved. Finally, the most effective factors were prioritized based on the output of the simulation software. The study was carried out during 2018 to 2019.

MATERIALS AND METHODS

Software selection

There are many strategies for evaluating the energy consumption of a building and measuring its energy efficiency. One of these strategies is building construction and application of measurement devices for collecting internal temperature, amount of the internal energy consumption and other climate and energy parameters of the building. Building construction and measurement of the design theories have high costs. Nowadays, if modeling and analysis tools are used tools during the design, the energy consumption will be able to evaluate for the building and its efficiency (Ashrae Committee, 2013; Amani and Kiaee, 2020). There are various types of software for modeling the building energy and its measurement. However, based on the need for evaluating the total building energy, defining the HVAC system and estimating the effects of sunlight and climate factors on the building, the Design Builder software was selected in this study. Design Builder - which is the most advanced and powerful software for energy modeling - was utilized as a research tool. Since it has the ability to model all aspects of the building, it was also used to simulate the building from different aspects such as building materials, building architecture, cooling and heating systems, lighting systems, home appliances, hot water consumption, etc. (Baghaei Daemei *et al.,* 2016; Yang and Zhang

Table 1: Previous studies on building energy efficiency using the energy simulation software

Type of buildings	Climate	Focus of paper	Simulation tools	References
Highly glazed buildings	Hot and humid	Assessment of the design of an adaptive biomimetic facade as a practical solution for enhancing energy efficiency.	Revit-2016 Ecotect-2011	Sheikh and Asghar, (2019)
Factory buildings	Temperate	Improvement of prevailing methodologies used in the assessment of energy efficiency	Energy building simulation	Weeber *et al.*, (2018)
Residential building	Mild	Providing a model based on Integrated Nested Laplace Approximation to predict the energy performance	Design Builder Energy Plus	Braulio-Gonzalo *et al.* (2016)
Residential building	Hot, sultry summers and cold, foggy winters.	A multi-criteria approach based on multi-attribute utility theory to assess alternative energy efficiency measures, explicitly considering both environmental and economic criteria.	Design Builder Energy Plus	D'Agostino *et al.* (2019)
Traditional building	Hot-dry	Assessment of the effects of building form and settlement texture on heating and cooling loads	Design Builder Energy Plus	Kocagil and Oral. (2015)
Historical building	Hot desert	Assessment of energy efficiency in Egypt	eQuest Design Builder Energy Plus	Fahmy *et al.* (2019)
Residential building	Warm temperature	Impact of VGS on building energy performance.	Design Builder Energy Plus	*Kalani et al.* (2017)
Residential building	Tropical equatorial	Benchmarking of residential buildings in Brunei Darussalam	Design Builder Energy Plus	Shabunko *et al.* (2018)
Residential building	Oceanic, cool and humid	Assessing the potential impact of a compartmentalization system retrofit strategy on energy	Design Builder Energy Plus	Carlsson *et al.* (2019)
Residential building	Both warm and moist climates	Simulating occupant behaviour on air conditioning	Design Builder Energy Plus	Yao (2018)
Residential, small office and large office buildings	Temperate	Urban-scale building energy consumption database assessed by Energy Plus models	Design Builder Energy Plus	Ding *et al.* (2019)
-	Temperate	Assessment of building energy efficiency rate using simulation tools	BIM Design Builder Energy Plus	No (2012)
Office buildings	16 locations of different climates	Investigation of energy savings potential of several common HVAC system re-tuning measures	Design Builder Energy Plus	Fernandez *et al.* (2015)
Residential building	1) Hot and humid 2) Mild and dry 3) Dry and cold	Reduction of energy consumption by green roofs in three different climates of Iran	Design Builder Energy Plus	Ebadati and Ehyaei (2018)

2015). Design Builder 4.2 software works based on computational engine of Energy Plus 8.3 and is capable of calculating the amount of ambient energy absorption during a year, calculating the amount of energy loss, separating energy consumption from functions of heating and cooling, designing and calculating the awnings, designing and defining HVAC, defining the solar systems such as solar cell and solar collector, optimizing and estimating the light, etc. This software can compute based on Ashrae 90.1 and 2007, 2010. To obtain .epw file for energy calculations in the coordinates and regions which were are not in the database of the Design Builder software, Meteororm 7 software was utilized as a maker of the Design Builder software. Moreover, the Climate Consultant software was used to obtain the thermal comfort and the earth temperature in the site. The method used in this study followed three steps: 1) Energy optimization actions in the building; 2) Estimation and evaluation of energy by the software

according to the optimal actions; 3) Prioritization of the factors affecting the energy consumption.

RESULTS AND DISSCUSSION

Climate data

To obtain .epw file for energy calculations in the coordinates and regions which were not in the database of the Design Builder software, Meteororm 7 software was utilized as a maker of the Design Builder software. Moreover, the Climate Consultant software was used to obtain the thermal comfort and the earth temperature in the site. In Chalous city, the summers are hot, muggy, dry, and clear and the winters are long, cold, and partly cloudy. The temperature typically varies within 42-88 °F and rarely drops below 34 °F or exceeds 92 °F during the year (Fig. 1).

The warm season (from June 5 to September 22) lasts for 3.6 months and has an average daily temperature of over 81 °F. The hottest day of the year is August 6, with the highest and the lowest temperatures of 88 °F and 77 °F, respectively. The cold season (from December 4 to March 25) lasts for 3.6 months and has an average daily temperature of below 59 °F. The coldest day of the year is January 29, with the lowest and the highest temperatures of 42 °F and 52 °F, respectively (Fig. 2).

As can be seen in Fig. 2, the average high (red line) and low (blue line) temperatures in day are within 25th-75th and 10th-90th percentile bands respectively. The thin dotted lines are the corresponding average temperatures perceived. Fig. 3 shows a brief characterization of the entire year with average hourly temperatures. The horizontal axis is the day of the year, the vertical axis is the hour of the day, and the color is the average temperature for the given hour and day.

Site position

Namakabroud town is located at a distance of

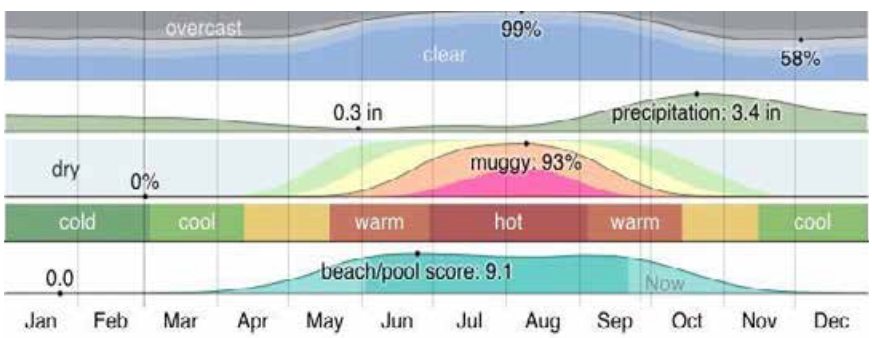

Fig. 1: Weather data of Chalous city

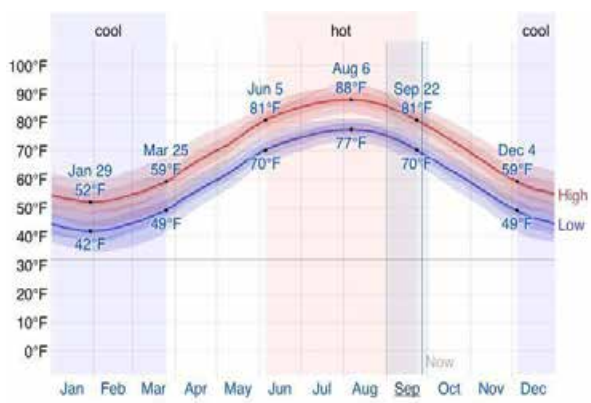

Fig. 2: Average high and low temperature

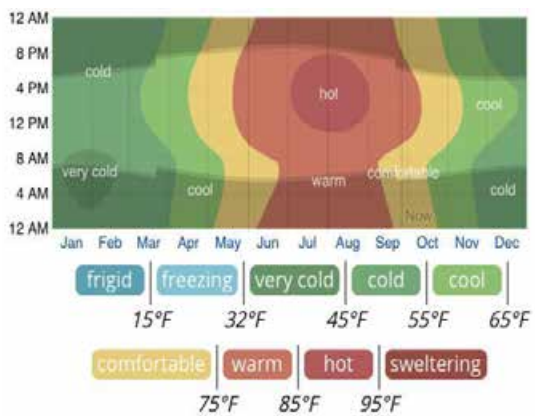

Fig. 3: Average hourly temperature

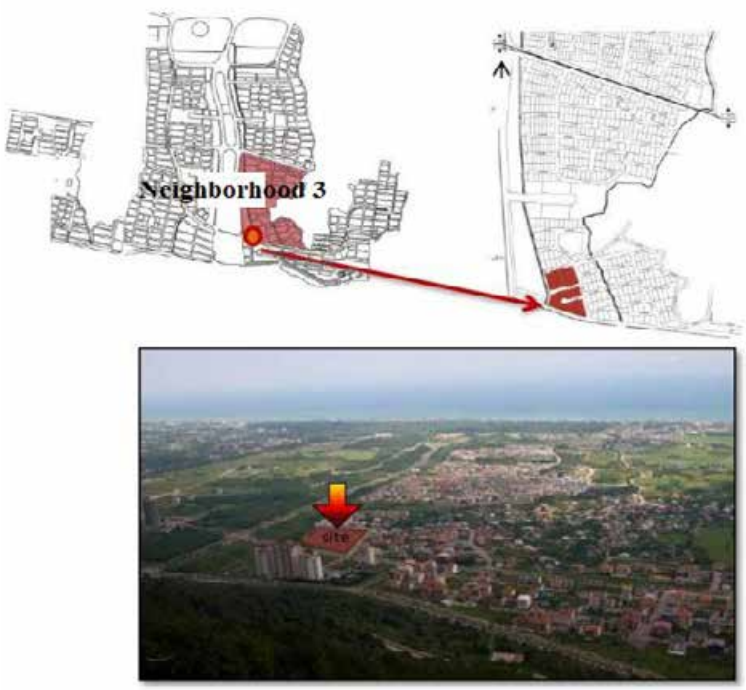

Fig. 4: Position of the studied site in Namakabroud city

92 km from the west of Chalous in Mazandaran province. It is restricted to the Caspian Sea in the north, to Alborz mountain range in the south, and to the agricultural lands in the west and east. The town has been designed on an area of 651 hectares and different phases of executive operations in it are currently in progress. It consists of five residential neighborhoods with recreational, athletic, service, commercial, cultural, religious, health and education centers (Namakabroud, 2018). The project is located at the south of neighborhood 3 in the residential tower site. This neighborhood, with an area of over 367,000 m^2, is located in the east of the town and reaches neighborhood 2 in the south (Namakabroud, 2018). Fig. 4 shows the location of the studied site.

The surrounding area of the site is mainly used for residential purposes and covered with villas and towers. Some parts of these residential spaces have not been constructed.

Building information

The initial steps in optimization of energy consumption are modeling of the climate and calculation of the amount of energy consumption in the building at different periods of the year. These steps require a comprehensive information about dimensions of the building, walls and equipment (Kharbouch *et al.,* 2017). The case study, with an area of about 200 m^2, is a residential building located in the Namakabroud, Chalous (Fig. 5). This building has a capacity for 5 persons and has two floors with 3 bedrooms, a living room, a kitchen, a restroom, a bathroom and a terrace exposed to fresh air in three directions. This study was performed in two fundamental steps. First, the amount of energy consumption in the base conditions was calculated, and next, the amount of energy consumption in the optimum conditions was calculated using the optimization strategies. Fig. 5 and Table 2 represent the plan of the building before making the modifications for optimization of energy consumption.

Building orientation

Orientation of the building has a very significant role in supplying a part of thermal requirements of the internal sections naturally. The sunlight received by the building surface and the heat produced during the day can provide a large amount of the required

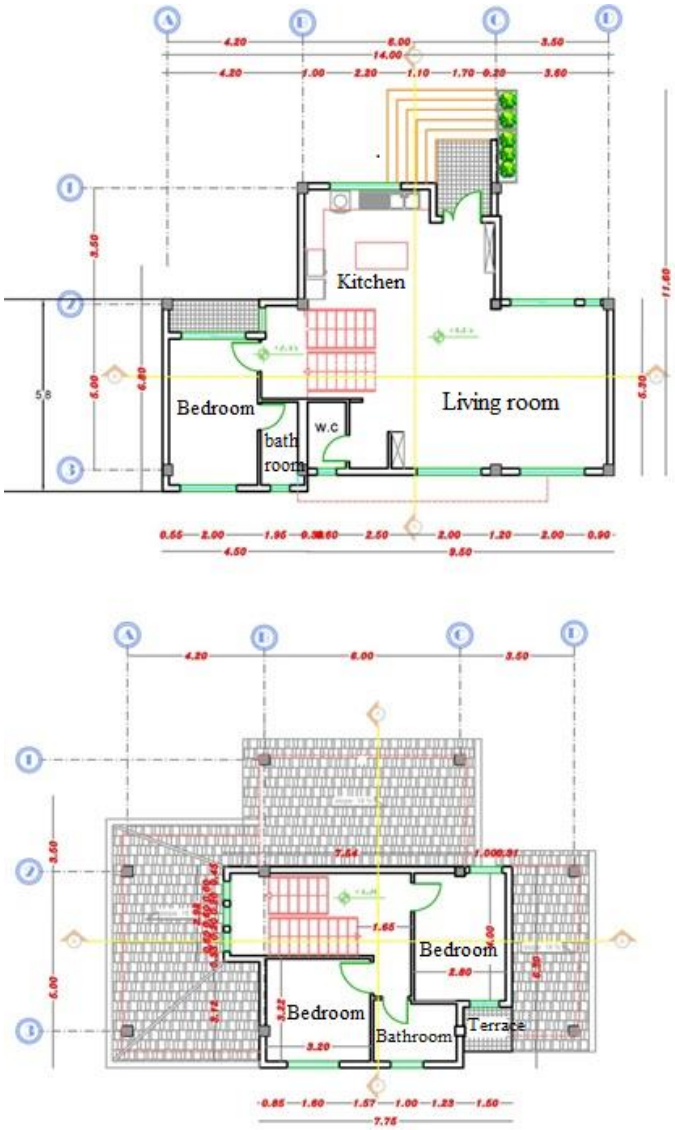

Fig. 5: Plan of the first and the second floors of the building in the base conditions

Table 2: Definition of the materials

Residential building materials before modifications	
Wall	Repairing the cement mortar, ceramic brick, plastering
Window frame	Aluminum without thermal bridge
Glaze	Single-glazed clear glass without awning
Celling	Asphalt, concrete slab, plastering
Residential building materials after modifications	
Wall	Repairing the cement mortar, ceramic brick, polyurethane foam, Plastering
Window frame	UPVC
Glaze	Double-glazed clear glass without awning
Celling	Asphalt, concrete slab, polyurethane foam, plastering

energy in the building (Amani and Soroush, 2020). The building orientation towards south is very effective in utilizing solar energy. Therefore, the southern walls where the sunlight is pass through or in the coldest day of the year from 9 AM to 3 PM contribute to higher utilization of the sunlight. Furthermore, the position of the building is important in protecting the building against undesirable winds during the year. On the other hand, the desirable winds are used to provide natural ventilation and reduce the inside temperature (BNRI, 2010). Using the software features, the climate file of Namakabroud was obtained by entering the geographic coordinates, the height above sea level and other information such as beginning and end of winter, beginning and end of summer, etc. Using the geographical files and the sub-components, the software can determine the best orientation of the building in degree (Saleh Ahangar, 2015). According to the software calculations in the given climate, the building was planned and established in the eastern-western direction between the angles of 10-15° to the west axis and 45° to the east axis. To provide the best thermal conditions inside the building, the frontage was oriented towards the south.

Energy optimal actions in building

The energy conservation opportunities, called ECO, are a set of actions that lead to the reduction of the energy consumption in the building. The principle idea in ECO is to permit daylight, heat and air flow to enter the building only when they are useful and to eliminate them when they are not useful (IjazIqbal *et al.,* 2018). In this study, optimization of energy consumption was performed into 7 steps:

1) Insulating the external walls of the building: The walls are able to save the heat because of having a high thermal capacity (the high mass). The heat or cold in the space can be saved in the mentioned elements and emitted into the environment when they are needed. In this way, the extreme temperature fluctuation inside the building is decreased. Requirements of the thermal elements with a high thermal capacity depend on the types of space. In the spaces that are continuously used round the clock, a high thermal inertia is obtained and a thermal insulation for the external side of the building shell is recommended. In the spaces with a discontinuous round the clock use, the thermal inertia should be as low as possible and a thermal insulation for the internal side of the building shell is recommended (BNRI, 2010). Considering the residential usages in this study, a polyurethane foam insulation with a thickness of 20 mm and a specific weight of 25 kg.m^3 was utilized in the external walls and ceiling. In the base conditions, the wall materials were transferred from the external layer to the internal layer, and repairing with the sand cement mortar 1, ceramic brick 20 and plastering 4 was performed (heat transfer coefficient was U = 1788). In the optimum conditions, the wall materials were transferred from the external layer to the internal layer and repairing with sand cement mortar 1, ceramic brick 10, polyurethane foam 2, brick 5 and plastering 4 was rendered (heat transfer coefficient was U = 0.831).

2) Using double-glazed windows: Since thermal insulation of glass is low, windows play an important role in energy loss. Application of double-glazed windows can decrease the cooling and heating loads by decreasing the load obtained from the natural air infiltration, reducing the glass conductive load, reducing the glass radiant load (Zakeri-Khatir *et al.,* 2015). In this study, in the base conditions, the building windows had single-glazed clear glasses with the heat transfer coefficient of U = 5778 and the frame materials were made up of aluminium without thermal bridge with the heat transfer coefficient of U = 5881. In the optimum conditions, the double-glazed clear glasses with the heat transfer coefficient of U = 2665 and UPVC frame materials with the heat transfer coefficient of U = 3476 were used.

3) Constructing the terrace on the north and south sides: Natural ventilation is highly important in obtaining a maintainable building. Terrace is a different architectural element regarded as an interface for natural ventilation and reduction of energy consumption in the building. It is of high importance due to providing the residents with temperature comfort by presenting a better ventilation and also preventing the use of ventilation devices. In this study, the intended building had no terrace in the base conditions. However, in the optimum conditions, it was analyzed after including two terraces on the north and south sides.

4) Using the internal venetian blind: Another way for decreasing energy consumption (only applied in the warm season and cooling load reduction) is to add internal awnings to all windows based on time schedule. In the base conditions, no internal blind

was considered, while in the optimum conditions, a Louvre Drape blind with medium transparency and open texture was used.

5) Using external movable awning: The thermal effect of direct sunlight which passes through a glass wall or a window without an awning is very significant. If a window does not have an awning or its awning does not have any effect, the sunlight will pass through the window and directly influence the internal space by its thermal effects. The heat produced in the internal space would be preserved inside the building by glasses, and by continuous radiation of sunlight into the building, the internal temperature would be increased excessively. Adding external awnings to all the windows would decrease energy consumption and is performed only in the warm season and for reduction of cooling load. When natural light is utilized in the warm season, these awnings protect the building from direct sunlight. The awning protrusion is 1 m above and beside the windows.

6) Using smart lighting control: Using lamps along with lighting can produce a great heat and this heat can contribute to heating the home in the winter. Since they extremely increase the cooling load in the summer, it is recommended to use the LED lamps, which have lower electricity consumption and heat production, in the lighting.

7) Reducing the total area of the windows: The amount of sunlight passes through the window is very important in terms of heat transfer. If the amount of the sunlight passes through the window is less than that of the heat transfer to the outer shell, the heat transfer will be reduced. The adequate level of sunlight supplied for internal spaces is responsible for decreasing the heat transfer to the outside (Zhang *et al.,* 2011). Decreasing the total area of the windows in a building can always be contemplated as an effective conservation opportunity. The higher heat transfer in the window rather than in the wall is mainly due to: 1) the lower conductive heat transfer coefficient of the walls compared to the windows, and 2) the relatively higher sunlight heating load transfer in the windows rather in than the walls in the summer. The heat transfer coefficient of a normal wall is in the range of 0.5 and 3 and the heat transfer coefficient of a normal window is in the range of 2.5 and 5 $W.m^2$ for 1 °C of temperature difference. In this study, the ratio of window to wall reduced from 20.5% to 14%.

Energy estimation

It was attempted to evaluate the amount of the energy required for the building during the year. For this purpose, the design assumptions such substituting the double-glazed UPVC window with the single-glazed aluminum window, utilizing the polyurethane foam insulation with thickness of 20 mm instead of the brick walls without isolation, using an internal Louvre Drape blind based on schedule to decrease the absorption of heat and sunlight in the summer, utilizing external movable awning to provide shadow in the summer, decreasing the ratio of window to wall from 20.5% to 14%, and placing the terrace in the north and south sides according to the available technical maps were assessed. To measure the energy consumption of the building and the optimum amount, the variables and assumptions were applied based on the standard model of ASHRAE 140-2007. The effects of modifications on energy consumption are listed in Table 3 and Fig. 6.

Cost benefit analysis

Iran has a variety of climates due to its large area. Due to the fact that energy consumption is proportional to the climate, the Ministry of Energy of Iran has divided the country into four tropical regions. Table 4 shows these regions and their warm months. The study area falls within tropical region 4. To calculate the electricity price, the Ministry of Energy of Iran published the tariffs in tropical region 4 in 2018 (Tables 5 and 6) (Ministry of Energy, 2018).

In bills of the tropical regions with warm and non-warm days, energy consumption is calculated based on the coefficients presented in Table 4 (Minstry of Energy, 2018). The average price of energy consumption per kWh in a year can be calculated using the data given in Tables 4, 5 and 6. As previously shown in Table 3, the amount of total energy consumption in the building was 6544.42 kWh per year before the optimization modifications. Therefore, the price of the bill could be calculated from the consumption line of 500 to 600 kWh per month presented in Tables 5 and 6. According to the specifications expressed by the Ministry of Energy, in tropical region 4, three months were considered to be warm, and nine months were regarded non-warm. Considering the coefficients for the warm and non-warm months in Table 4, the average price of annual energy consumption for the consumer was calculated

Table 3: The effects of modifications on energy consumption based on the type of modification

Modifications	Before modifications	After modifications	Amount of kWh variation	Amount of reduction (%)	Cost benefit ($US)
Changing the materials - Transferring from the external layer to the internal layer - The unit of the thickness is cm. - Unit U= w/m2-k	Wall materials: Repairing the cement mortar (1), ceramic brick (20), plastering (4), U=1.788 Ceiling materials: Asphalt (1), concrete slab (20), plastering (4), U=2.518 Window materials: Single-glazed clear glass without awning (0.6), Sgl Clr 6 mm, U=5.778 Frame materials: Aluminum without thermal bridge, U=5.881 Total cooling and heating energy: 3074.27 kWh	Wall materials: Repairing the cement mortar (1), ceramic brick (10), polyurethane foam (2), brick (5), plastering (4), U=0.831 Ceiling materials: Asphalt (1), concrete slab (20), polyurethane foam (2), plastering (4), U=0.900 w/m2-k Window materials: Double-glazed clear glass without awning, Dbl Clr 6 mm/13 mm air, U=2.665 w/m2-k Frame materials: UPVC, U=3.476 Total cooling and heating energy=2304.27 kWh	770 (kWh)	25.05%	1250.26 $US
External movable awning and internal blind	Does not have Total cooling and heating energy: 3074.27 kWh	External awning for the summer with a protrusion of 1 Louvre Drape blind with medium transparency and open texture inside the building. Control: Sensitive to external temperature and amount of sunlight: base temperature of outside: 22°C/amount of base sunlight: 120 W.m^2 Total cooling and heating energy: 2972.77 kWh	101.5 (kWh)	3.3%	903.25$US
Lighting lamp	Fluorescent Total lighting energy: 3470.15 kWh	LED Total lighting energy: 2489.45 kWh	980.4 (kWh)	28.26%	1469.16 $US
Window-to-wall ratio (WWR)	WWR: 20.5% Total cooling and heating energy: 3074.25 kWh	WWR: 14% Total cooling and heating energy: 3004 kWh	70.27 (kWh)	2.3%	887.03$US
Northern and southern terrace	Does not have Total cooling and heating energy: 3074.27 kWh	Has base on plot proportions Total cooling and heating energy: 3062.52 kWh	11.75 (kWh)	0.3%	856.68$US
Amount of variations	Heating and cooling: 3074.27 Lighting: 3470.15	Heating and cooling: 1939.91 Lighting: 2489.45	1134.36 (kWh) 980.40 (kWh)	36.90% 28.26%	1439.39 $US 1469.16 $US
Total amount of variations	6544.42 kWh	4429.36 kWh	2115.06 (kWh)	32.32%	2908.55 $US

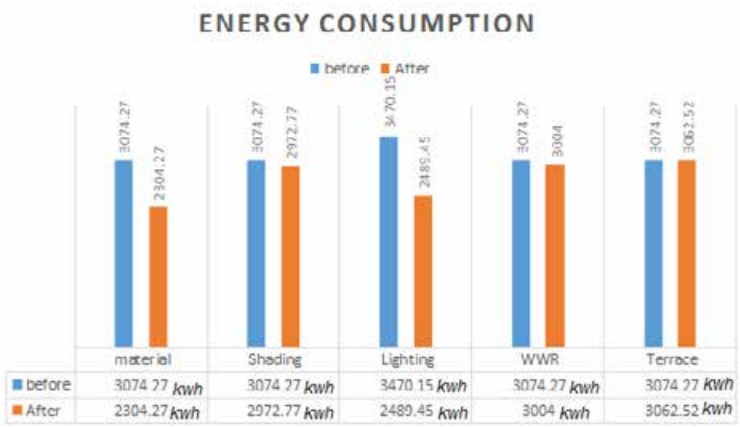

Fig. 6: The effect of modifications on energy consumption based on the type of modification

as $US 0.80 per kWh using Eq. 1.

[(0.80 ($US) * 9 * 1) +(0.61 ($US) * 3 * 1.3)]/12=$US 9.5/12=$US 0.80 (1)

After the optimization modifications, the amount of total energy consumption in the building was obtained as 449.36 kWh per year (Table 3). Therefore, it was possible to calculate the price of the bill from the consumption line of 300 to 400 kWh per month presented in Tables 5 and 6. Based on the specifications proposed by the Ministry of Energy, in tropical region 4, three months were considered to be warm, and nine months were regarded non-warm. Considering the coefficients for the warm and non-warm months in Table 4, the average price of annual energy consumption for the consumer was estimated as 0.52 $US per kWh using Eq. 2.

[(0.55 ($US) * 9 * 1) + (0.32 ($US) * 3 * 1.3)]/12 =6.23 ($US)/12=$US 0.52 (2)

The costs of electricity consumption before and after modifications were estimated to be $US 5207.7 and $US 2299.2, respectively. Moreover, the saving rate was calculated as 2908.5 $US. The cost saving was calculated for each item separately.

Table 4: Coefficients for calculation of bills in tropical regions

Tropical regions	Coefficient of warm months	Coefficient of non-warm months
Tropical region 1	4	1
Tropical region 2	3	1
Tropical region 3	2	1
Tropical region 4	1.3	1

Table 5: Tariffs for non-warm months in tropical region 4

Average monthly energy consumption (kWh)	Basic price per kWh ($US)
0 to 100 (kWh)	0.12
Surplus 100 to 200 (kWh)	0.14
Surplus 200 to 300 (kWh)	0.30
Surplus 300 to 400 (kWh)	0.55
Surplus 400 to 500 (kWh)	0.63
Surplus 500 to 600 (kWh)	0.79
Surplus 600 (kWh)	0.87

Table 6: Tariffs for warm months in tropical region 4

Average monthly energy consumption (kWh)	Basic price per kWh ($US)
0 to 100 (kwh)	0.09
Surplus 100 to 200 (kWh)	0.11
Surplus 200 to 300 (kWh)	0.20
Surplus 300 to 400 (kWh)	0.32
Surplus 400 to 500 (kWh)	0.46
Surplus 500 to 600 (kWh)	0.61
Surplus 600 (kWh)	0.73

Table 7: Prioritization of the optimization strategies for energy consumption in the building according to the amount of energy reduction in each section

Design strategy	Amount of reduction in energy consumption (kWh)	Percentage of reduction in energy consumption
LED lamp	980.4 (kWh)	26.26%
Using window and thermal insulation in walls and ceiling	770 (kWh)	25.05%
External and internal awning	101.5 (kWh)	3.3%
Reducing the window area	70.27 (kWh)	2.3%
Terrace	11.75 (kWh)	0.3%
Total variation	2115.06	32.32%

Prioritizing the effective factors in energy consumption

In the first step, the energy consumption was estimated in the base conditions, and in the second step, the amount of energy consumption in the optimum conditions was calculated. The software calculations and comparison of them showed that the proposed strategies can lead to 32.32% reduction in the annual energy consumption (Table 3). The obtained results indicated that application of the LED lamps instead of the conventional fluorescent lamps had the most significant effect on reduction of energy consumption and could reduce it by 980.4 kWh (28.26%). Changing the materials of the walls and ceiling, using the polyurethane foam insulation with the thickness of 20 mm and application of double-glazed UPVC windows led to 770 kWh (25.05%) reduction in energy consumption and were considered as the second priority. Compared to other methods, awning did not have a significant effect on reduction of energy consumption and it was considered as the third priority. Since the external movable awning along with internal blind resulted in 101.5 kWh (3.3%) reduction in energy consumption, its application seemed to be unnecessary in all the climatic regions. To determine the necessity of using the awning, the climate of the region must be precisely studied for warm hours in a year. To avoid a warm house, all window should be placed in shadow at different sides of the building based on the warm hours of the year and the angle of sunlight. Decreasing the area of windows was found to be in the fourth priority. Since reduction of the window area can reduce the energy consumption by 70.27 kWh (2.3%), the large- or small-sized windows, if placed in accurate orientations, may not have a significant effect on energy consumption. In both base and optimum conditions, the windows were oriented towards the best direction, and terrace had the least effect on energy consumption in the studied building. The southern and northern terraces decreased the energy consumption by 11.75 kWh (0.3%). Therefore, it was concluded that the existence of terrace in the given climate did not have a significant effect on energy consumption. The total heating and cooling variation in base and optimum conditions was 1134.36 kWh (36.90%). Moreover, the total lighting variation was 980.40 kWh (28.26%). Generally, the optimization strategies proposed in this study reduced the energy consumption by 2115.06 kWh (32.32%). Table 7 demonstrates the prioritization of the optimization strategies for energy consumption in the building according to the amount of energy reduction in each section.

Investigation of the previous studies published in popular databases (Table 1) revealed that no studies yet have been done on energy efficiency using prioritization of the effective factors in residential buildings based on the Design Builder simulation software. The results obtained in the present study showed that the used materials (with the exact specifications) have the largest effect on energy efficiency in the studied building (Table 3). The modifications carried out for optimization of energy consumption in the building were: changing the wall materials by adding polyurethane foam, using a UPVC window with double-glazed glass instead of a plain aluminum window with a single-glazed glass, application of an awning with 1 m protrusion, using Louvre Drape blinds with medium transparency and open texture, using the LED lamps instead of the conventional fluorescent lamps, reduction of the window to wall ratio from 20.5% to 14%, and designing the terrace at the northern and southern sides. Generally, the annual energy consumption was reduced from 6544.42 kWh before optimization to 4429.36 kWh after optimization. Simultaneous application of the proposed optimization strategies led to a saving of $US 2908. The software calculations showed that the thermal insulation with a thickness of 20-30 mm was the best option in the given climate according to the National Building Regulations-Energy Conservation data (Table 3) (BNRI, 2010). The results indicated that the thicknesses higher or lower than the mentioned range would not be optimal in terms of costs and energy saving in different seasons (winter and summer). The Design Builder software efficiently analyzed all data and the applied materials and provided the best output.

CONCLUSION

A residential villa in Namakabroud, Chalous was stimulated using the Design Builder software. For this purpose, the most commonly used materials in the building were analyzed by the Design-Builder software. The analysis was done by integrating building architecture engineering (the best form of orientation and facade). It was based on the reasonable costs of the common materials in the area. To provide the internal space with the best thermal conditions, the building frontage was designed toward the south. In the first step, the amount of energy consumption was calculated in the base conditions, and in the second step, the amount of energy consumption was estimated in the optimum conditions. The obtained results indicated that application of the LED lamps instead of the conventional fluorescent lamps, by reducing the energy consumption by 980.4 kWh, had the largest effect. Changing the materials of the walls and ceiling, changing the windows and frames, using the polyurethane foam insulation with the thickness of 20 mm and using a double glazed UPVC window, by reducing the energy consumption by 770 kWh, were in the second priority. The amount Application of the external movable awning and the internal blind, with an energy reduction of 101.5 kWh, had not a significant effect on energy consumption and was placed in the third priority. Moreover, reducing the total area of the windows was in the fourth priority. Finally, the presence of terrace had the lowest effect on energy consumption in the studied building. The results presented in this study can be useful in evaluating the energy efficiency in residential buildings and producing a comfortable living environment in north of Iran.

AUTHOR CONTRIBUTIONS

. Amani performed the conceptualization, methodology, investigation, validation, and supervision. F Tirgar Fakheri performed the data collection, software, simulation, and validation. K. Safarzadeh performed the literature review and writing - original draft.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

BIM	Building Information Modeling
Clr	Clear
Dbl	Double
ECO	Economic Cooperation Organization
Eq	Equation
epw	Economic and political weekly
HVAC	Heating, ventilation, and air conditioning
IV	4
LED	Light-emitting diode
Km	Kilometer
kWh	kilowatt-hour
mm	Millimeter
Sgl	Single
UPVC	Unplasticized polyvinyl chloride
WWR	Window-to-Wall Ratio
%	Percent
$US	Dollar United State
°F	degree Fahrenheit

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ORIGINAL RESEARCH PAPER

Biodegradable mulch as microclimate modification effort for improving the growth of horenso; *Spinacia oleracea* L.

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ABSTRACT

BACKGROUND AND OBJECTIVES: Increasing global temperature imposes large risks to food security globally and regionally. Besides, adaptation effort on cultivation practices, such as mulching, is urgent to overcome environmental problem due to certain material used, commonly plastic that is not biodegradable. Biodegradable mulch is a mulch that could be degraded by microorganism and made from renewable organic materials. It plays a role in carbon sequestration and will contribute carbon and nutrients to the soil after being degraded. This current research aimed at investigating soil microclimate under various biodegradable mulch compositions and optimizing the compositions of biodegradable mulch that can be used to support the growth of short-cycle crops i.e. horenso (*Spinacia olearecea* L.).

METHODS: This study was carried out using a simple randomized complete block design with one control (without mulch) and five treatments (biodegradable mulch compositions), namely the percentage of water hyacinth (40-80%) and coconut coir (20-60%).

FINDINGS: All tested biodegradable mulch compositions could modify microclimate by decreasing 1-2°C of soil temperature and maintaining the soil moisture within the range of 63-84%. Although there was no significant difference in the growth and yield of horenso among the differing biodegradable mulch compositions, the biodegradable mulch composition treatments resulted in signficantly higher value than the control (without mulch). The biodegradable mulch composition treatments could increase fresh shoot weight around 38-55%, fresh root weight for about 55-94%, and dry shoot weight approximately by 1.6-2.8 times compared to the control (without mulch).

CONCLUSION: This finding has emphasized that all tested biodegradable mulch compositions are potentially used as mulch for horenso *(Spinacia oleracea L.)* cultivation. This study provide information in the formulation of biodegradable mulch to adapt the compositions on other short-cycle crops and other horticulture crops.

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INTRODUCTION

Human activities have contributed about 1.0°C of rising global temperature over the pre-industrial levels and would reach 1.5°C in the next three decades (IPCC, 2018). Climate change affects food security and nutrition through its impact on food availability, quality, accessibility, and distribution. The rise of global temperatures leads to major risk on global and regional food security, especially in low-latitude areas, as the effects of temperature changes, precipitation, and extreme weather, as well as the increasing CO_2 concentrations (Gornall *et al.*, 2010; Ayinde *et al.*, 2011; Hoegh-Guldberg *et al.*, 2018). A healthy lifestyle is one of the precursors of the initiated habit of consuming fruits and vegetables, including spinach. National spinach consumption increased by 11.25% in 2015-2016, but the increased production, productivity, and harvested area, respectively, were only by 6.77%, 3.53%, and 3.13% (Ministry of Agriculture Republic of Indonesia, 2017). Asia produced most of the world's horenso in 2016-2018, approximately 95%, and the biggest importer was Europe, around 54-58% of world import quantity (FAO, 2020a and 2020b). Horenso *(Spinacia oleracea* L.) is one type of spinach with a higher economic value than other types commonly consumed by local people (Amaranth sp.). Global warming that has caused the evapotranspiration and respiration inflicts an impact on crop yields. An effort to overcome the problem is developing an appropriate technology through modifying the environment to provide a near-optimum growth environment for horenso plants i.e. mulching (Lalljee, 2013; Fagariba *et al.*, 2018). Mulch is commonly used in vegetable crop cultivation practices to manipulate the microclimate, increase water use efficiency, and improve growth and yields (Behzadnejad *et al.*, 2020; Edgar *et al.*, 2016; Henrique, 2020; Lamont, 2017; Sathiyamurthy *et al.*, 2017). Most mulch films are produced from petroleum-based plastics, generally polyethylene, and have caused waste handling problems (Kasirajan and Ngouajio, 2012). Plastics as synthetic polymers are non-biodegradable and the handling of their wastes constitutes the major problem. Furthermore, 8% of total world oil production is consumed in plastics manufacturing, in which 3-4% is used as energy during the production process, and thus indirectly causing CO_2 emissions and global warming (Nkwachukwu *et al.*, 2013). Biodegradable mulch (BDM) is a mulch that could be degraded by microorganism and is made from renewable organic materials. In addition to its environmentally-friendly characteristic, BDM plays a role in carbon sequestration and will contribute carbon and nutrients to the soil after being degraded (Jirapornvaree *et al.*, 2017). Tanveer *et al.* (2019) asserted that mulch can protect the soil from excessive evaporation and increase soil organic matter (SOM) as a result of increasing carbon input and decreasing soil disturbance. It was emphasized that the application of mulch and plant residues has increased soil microbial activity, ameliorated heat stress, provided water storage, and increased soil organic carbon (SOC). Gu *et al.* (2016) reported that the application of mulch above ground level increases SOC contents and its active fractions at the depth of 1-100 cm. Hu *et al.* (2018) affirmed that the combination of green manure and mulching using crop residues in organic crop systems increased C input and SOC contents. Unfortunately, this benefit cannot be obtained from the use of plastic mulch because there is no additional C input nor increasing SOC mineralization (Wang *et al.*, 2016). Biodegradable mulch is a promising solution; therefore, a series of research on raw materials and their compositions has been initiated these past years. Some materials that have been studied are water hyacinth, straw, banana stem, tannery waste, recycled paper, cellulosic fiber, and starch (Iriany *et al.*, 2018; Iriany *et al.*, 2019a and 2019b; Zhang *et al.*, 2019; Henrique, 2020; Marí *et al.*, 2020). In this current research, water hyacinth was used because it is an aquatic weed that has high dry matter yield of approximately 400 kg/ha/week with a high total content of cellulose and hemicellulose (± 43%). In addition, coconut coir was used considering its inexpensive fiber sources from post-harvest coconut with low specific weight so that it has a good tensile strength (Tham, 2012; Sarika *et al.*, 2014; Salleh *et al.*, 2015). The optimum composition of BDM made from the combination of water hyacinth and coconut coir has not been reported yet; accordingly, its application to the crop cultivation, particularly initiated to short-cycle crop e.g. spinach, is required. Furthermore, understanding the role of BDM on microclimate modification is needed to contribute climate change adaptation strategy. The objectives of this current research were to investigate the soil microclimate under various BDM compositions and to optimize the BDM compositions that can be used to support

the growth of short-cycle crops, especially horenso. To achieve these objectives, the field experiment was conducted at East Java, Indonesia in 2019.

MATERIALS AND METHODS

This research was conducted at Dau, Malang, East Java, Indonesia with an altitude of 500 meters above sea level, the average daily temperature of 25-32 °C, and the rainfall of around 3600 mm per year. The physical and chemical properties of the soil shown in Table 1. Some materials used in this current research were raw materials of BDM (water hyacinth petiole and coconut coir), horenso seed *(Spinacia oleracea* L), and fertilizer (foliar fertilizer, manure, and green manure (Azolla sp). The procedures of making BDM were cutting and weighing, pulping, molding, and drying as explained by Iriany *et al.* (2018).

Experimental design

This research was carried out using a simple randomized complete block design (RCBD) with one control (without mulch) labeled as MO, and five treatments (BDM compositions), repeated three times. The treatments were various BDM compositions (the percentage of water hyacinth and coconut coir) labeled as MO1 (80:20), MO2 (70:30), MO3 (60:40), MO4 (50:50), and MO5 (40:60).

Measured variables

Measured variables included soil microclimate and plant growth. Microclimate was observed in the morning and at noon (also called as minimum and maximum for soil temperature variables), twice a week, using a digital thermohygrometer during horenso cultivation. Microclimate variables were soil temperature (°C) and soil humidity (%). The plant growth variables were plant height (cm), number of leaves, leaf area (cm^2), and stem diameter (mm), observed once a week from 1st until 5th week after planting (WAP). Marketable yield and dry weight of horenso included fresh shoot and root weight (g) and dry shoot and root weight (g), harvested in the end of observation.

Table 1: Soil physical and chemical properties

Soil properties	Value
Bulk density (g/cm^3)	1.27
Porosity (%)	51.24
Sand (%)	45.09
Silt (%)	41.01
Clay (%)	13.90
Water content at pF 2.5 (cm^3/cm^3)	0.30
Water content at pF 4.2 (cm^3/cm^3)	0.17
Macropores (%)	30.80
Mesopores (%)	12.90
Micropore (%)	8.80
pH	5.96
Soil organic (%)	4.07
N total (%)	0.34
P-available (mg/kg)	41.63
K (mg/100 g soil)	57.69
CEC (cmol(+)/kg)	38.95

Statistical analysis

The data were analyzed using the analysis of variance (ANOVA) to determine the effect of the treatments, then by means of HSD (Tukey test) α 5% to find out the best treatment. Correlation analysis was performed to understand the relationship between plant growth and microclimate (soil temperature and moisture). Response surface method (RSM) analysis was also carried out to analyze the optimum BDM compositions based on fresh shoot weight and plant height data using Minitab v19.

RESULTS AND DISCUSSION

Soil microclimate under various biodegradable mulch compositions

The average of minimum soil temperature under BDM was 25°C and the average of maximum soil temperature was 28°C; while the averages of minimum and maximum soil temperatures in bare soil (control) were 27°C and 28°C respectively. Soil moisture ranged between 75-84% with the average of 80% in the morning and ranged between 63-80% with the average of 73% at noon after the application of various BDM compositions. Soil moisture in bare soil (control) ranged between 60-70% with the average of 66% in the morning and ranged between 51-66% with the average of 57% at noon (Fig. 1). All tested biodegradable mulch compositions in this study could modify microclimate by decreasing 1-2°C of soil temperature and maintaining the soil moisture within the range of 63-84%. This result was in accordance with previous research reported by Iriany *et al.* (2019a) that the soil temperature under BDM made from water hyacinth and banana stalk were lower and more stable compared with without mulch and the soil humidity was within the range of 66.1 - 78.2%.

The optimum temperature of baby leaf spinach cultivation according to Applied Horticultural Research (2016) ranges between 14-24°C with the maximum temperature of 32°C. This condition is even more fulfilled by the use of BDM, with the minimum temperature of 25°C and the maximum temperature of 28°C compared to the control with the minimum and maximum temperatures of 27°C and 28°C respectively. Yamori *et al.* (2005) reported that the optimum temperatures of light-saturated photosynthetic rate of spinach leaves were 27°C, 36°C, and 24°C at the ambient CO_2 concentration of 360 µL/L, 1500 µL/L, and a curve of 50, 100 and 150 µL/L at the high-temperature treatment (day/night i.e. 30/25°C). The use of various BDM compositions could modify the microclimate i.e. decreasing the soil temperature by 1-2°C and maintaining the soil moisture within the range of 63-84%. This result was similiar to a research reported by Chen *et al.* (2015) that there was a reduction of soil temperature under straw mulch application between rows of wheat due to the prevention of direct high solar energy from reaching the furrow soil. Kumar and Dey (2012) explained that the reduction of maximum soil temperature, with application of hay mulch, might be attributed to the higher albedo and the rise in heat transfer diffusion.

Plant growth of horenso (Spinacia oleracea L.) on various biodegradable mulch compositions

The effects of BDM compositions on the plant height of horenso started to appear on 2 and 3 weeks after planting (WAP). On the 4 and 5 WAP, various BDM compositions did not significantly affect the height of horenso although there were significant differences compared to the control (without mulch) (Fig. 2). Based on Spinach Plants, Spinach Leaves, and Bunched Spinach: Shipping Point and Market

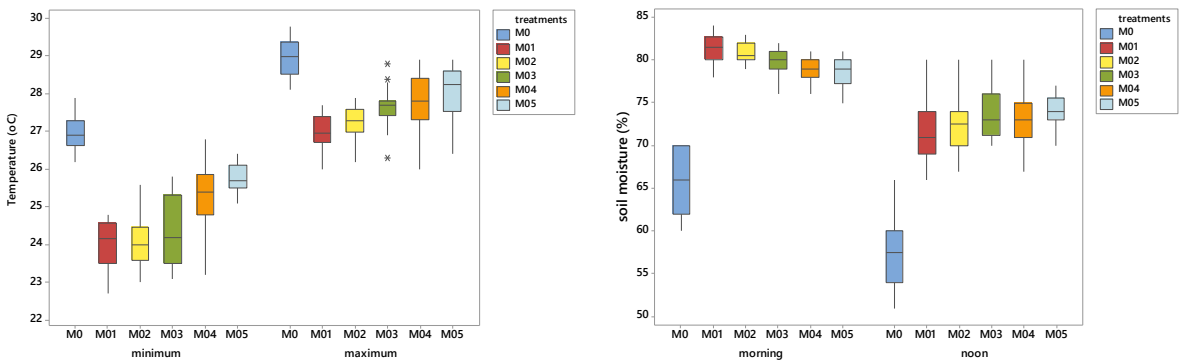

Fig. 1: Minimum and maximum soil temperatures and soil moisture after the application of various BDM compositions

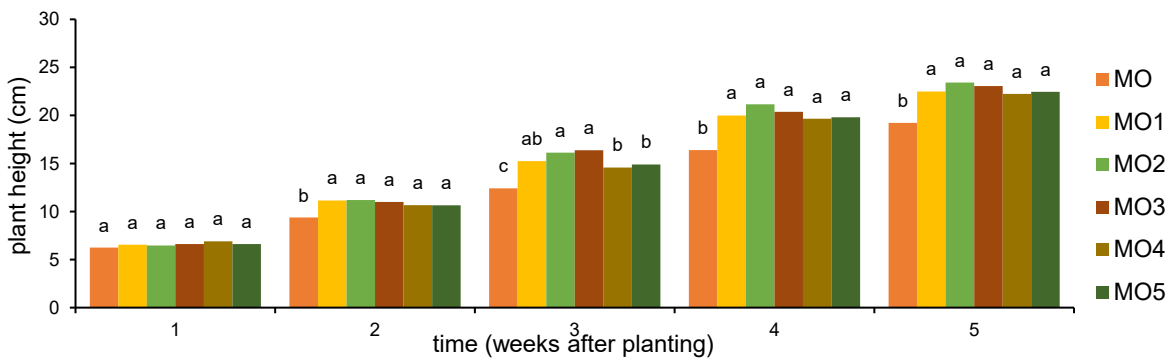

Fig. 2: Plant height of horenso *(Spinacia oleracea* L.) grown in various BDM compositions on 1 until 5 WAP. The same letters on the top of bar in the same WAP show insignificant difference at P≤ 0.05 based on HSD test

Inspection Instructions, plant height at 5 WAP had met spinach medium standard (4-8 inches or 10.16-20.32 cm) to large standard (> 8 inches or 20.32 cm) (USDA, 2006).

The effects of BDM compositions on the number of leaves began to be seen on 2 WAP to 4 WAP and showed higher value than the control (without mulch) (Fig. 3). The BDM composition treatments did not contribute significant effects on the number of leaves at the end of the observation although the BDM composition treatments resulted in more leaves than those of the control.

The effects of treatments on leaf area were seen on the 1st WAP with MO1 treatment showing the highest average of leaf area compared to the other BDM compositions. On 4 and 5 WAP, MO2 treatment showed the highest average leaf area compared to the other BDM compositions and the control (Fig. 4).

The effect on the stem diameter was shown on 2 WAP with MO1 treatment, detecting wider stem diameter than the other BDM compositions. On 3 WAP until the end of the observation, there was no significant difference in stem diameter among differing BDM compositions; however, there were significant differences between the BDM compositions and the control (Fig. 5).

The results of observation on marketable yield and dry weight of horenso (25 days after planting (DAP)) showed that the treatments significantly affected fresh and dry shoot weight as well as fresh root weight variables, but not on the dry root weight (Table 2). The BDM composition treatments could increase fresh shoot weight around 38-55%, fresh root weight for about 55-94%, and dry shoot weight approximately by 1.6-2.8 times compared to the control (without mulch).

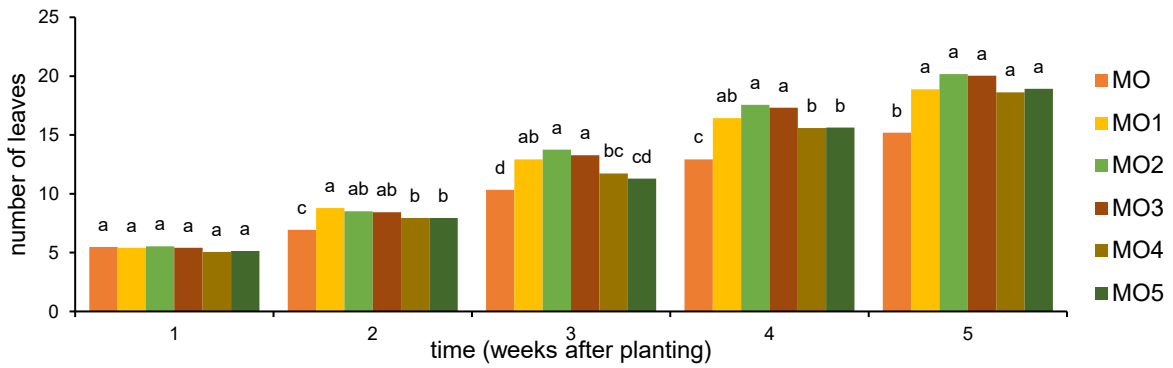

Fig. 3: Number of leaves of horenso (Spinacia oleracea L.) grown in various BDM compositions on 1 until 5 WAP. The same letters on the top of bar in the same WAP show insignificant difference at P≤ 0.05 based on HSD test

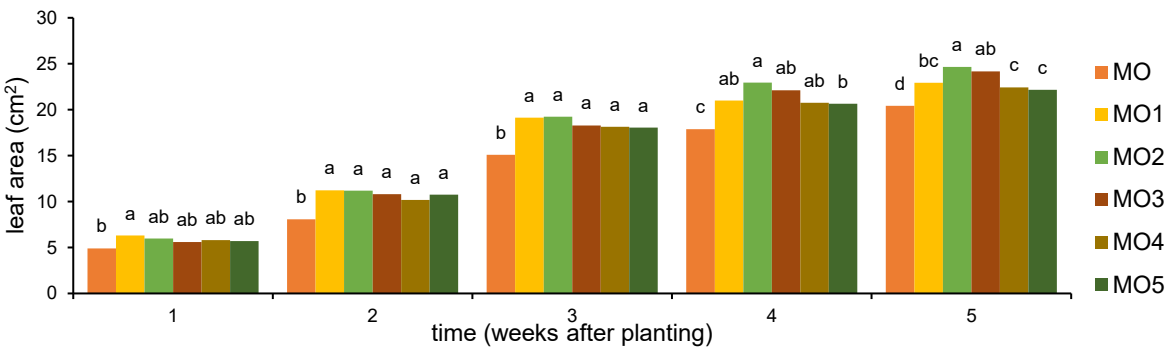

Fig. 4: Leaf area of horenso *(Spinacia oleracea* L.) grown in various BDM compositions on 1 until 5 WAP. The same letters on the top of bar in the same WAP show insignificant difference at P≤ 0.05 based on HSD test

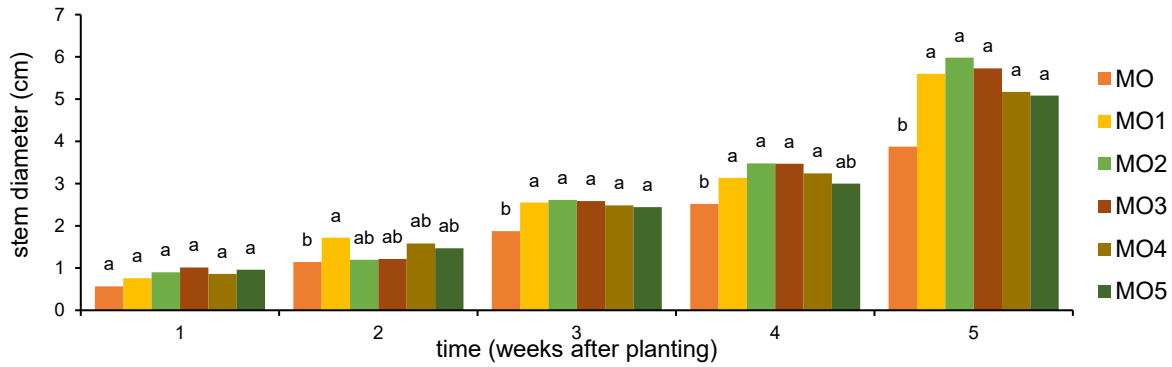

Fig. 5: Stem diameter of horenso *(Spinacia oleracea* L.) grown in various BDM compositions on 1 until 5 WAP. The same letters on the top of bar in the same WAP show insignificant difference at P≤ 0.05 based on HSD test

Table 2: Marketable yield and dry weight of horenso grown in various BDM compositions at 25 days after planting (DAP)

Treatment	Fresh shoot weight (g)	Dry shoot weight (g)	Fresh root weight (g)	Dry root weight (g)
MO	6.88 b	0.73 b	3.27 d	0.53 a
MO1	9.58 a	1.88 ab	5.17 c	0.29 a
MO2	10.63 a	2.17 a	6.32 a	0.61 a
MO3	10.10 a	2.53 a	6.03 ab	0.42 a
MO4	9.45 a	1.91 ab	5.25 bc	0.43 a
MO5	9.54 a	2.76 a	5.07 c	0.48 a

Mean values in same columns followed by the same letter are not significantly different at P≤0.05 significance based on HSD (Tukey test α= 0.05).
MO (control/bare soil), BDM compositions (the percentage of water hyacinth and coconut coir) labeled as MO1 (80: 20), MO2 (70:30), MO3 (60:40), MO4 (50:50), and MO5 (40:60).

Table 3: Coefficient correlation (*r*) between microclimate and growth variable

Variable	Leaf area	Stem diameter	Number of leaves	Plant height	Fresh SW	Dry SW	Fresh root weight	Dry root weight
T_{min}	-0.805**	-0.775**	-0.788**	-0.757**	-0.728**	-0.435*	-0.809**	0.212^{ns}
T_{max}	-0.685**	-0.767**	-0.757**	-0.768**	-0.738**	-0.433*	-0.758**	0.266^{ns}
SM_{mor}	0.739**	0.777**	0.889**	0.907**	0.844**	0.658**	0.865**	-0.156^{ns}
SM_{noon}	0.692**	0.751**	0.888**	0.856**	0.793**	0.711**	0.840**	-0.170^{ns}

T= soil temperature; $_{min}$= minimum; $_{max}$= maximum;SM= soil moisture; $_{mor}$= morning; SW= shoot weight
** = *P*-value ≤ 0.01; * = 0.01 < *P*-value ≤ 0.05; ^{ns} = *P*-value > 0.05

Based on the correlation analysis, the temperature component (minimum and maximum) has shown a considerably close relationship with the growth and marketable yield of horenso. In summary, the minimum and maximum temperatures have been connected to the growth and marketable yield variables; while the moisture of the morning and noon soil has shown a positive relationship with the growth and marketable yield variables (Table 3). These results could be explained by the improvement of the growth and marketable yield of horenso after the BDM composition treatments compared to the bare soil.

In general, various BDM compositions did not show significant differences in the growth variables of horenso (plant height, number of leaves, stem diameter, and fresh shoot weight). However, there were significant differences between the BDM composition treatments and the bare soil. The results of this current research were in accordance with the previous BDM-based research on shallot and cauliflower cultivation. BDM application (made from water hyacinth, straw, and tannery waste) on shallot resulted in insignificantly different fresh and dry weight among differing BDM compositions, but significantly different from the control (without

mulch) at 40 DAP (Iriany *et al.*, 2019b). In addition, the treatments of various BDM compositions (made from water hyacinth, banana pseudostem, and tannery waste) resulted in insignificant number of leaves on cauliflower (Iriany *et al.*, 2019a). The effects of the use of organic mulch from various sources on *Spinacia oleracea L.* cultivation have been widely reported. The use of organic compost mulch (400 grams per planting basin) increased fresh weight and dry weight of spinach by 8% and 12% respectively, compared to the bare soil (M Manyatsi and Simelane, 2017). In addition, Meena *et al.* (2014) reported that a more suitable microclimate condition, lowering the temperature by 2-6 °C at the depth 0-5 cm, resulted in the increase of fresh weight of spinach around 22-66%. Khan *et al.* (2019) assert that mulching using green tea waste-rice bran compost at the dose of 0.5 kg/m^2 increased dry weight of spinach by 2.5 times compared to the control (without mulch) and increased dry weight of radish by 0.8, 1.7, and 2.0 times compared to the control (without mulch) at the doses of 0.5, 1, and 2 kg/m^2 respectively. Carmichael *et al.* (2012) also confirmed that the use of mulch grass (10 cm thickness) significantly increased plant height and leaf area by 39% and 18% respectively, but it did not significantly increase fresh weight on 5 WAP (only 18%) compared to the bare soil in radish (*Raphanus sativus* L.) cultivation (with 70% soil moisture). The percentage increase in fresh and dry shoot weight of *Spinacia oleracea L.* reported in the previous research is still lower than the results of this current research. Accordingly, BDM made from water hyacinth and coconut fiber is promising to be used in *Spinacia oleracea L.* cultivation. Higher growth, marketable yield, and dry weight in all BDM compositions compared to the control (without mulch) can be specifically explained by microclimates, i.e. lower temperature under BDM compared to the bare soil. It can be caused by Rubisco (µmol/m^2) and cytochrome f per Rubisco content (mol/mol) (balancing between RuBP regeneration and RuBP carboxylation) at lower temperature that were higher compared to the higher temperature treatment (Yamori *et al.*, 2005).

Optimum biodegradable mulch for improving the growth of horenso (Spinacia oleracea L.)

Based on response optimizer, the optimum BDM composition affecting plant height, stem diameter, number of leaves, and fresh shoot weight as the response variables was obtained at 56.42% water hyacinth and 0% coconut coir with the composite desirability (D) value of 0.9620. The D values of the tested BDM compositions from the highest to the lowest were MO2, MO3, MO1, MO4, and MO5 respectively, with the values ranging from 0.8065-0.6211 (Table 4).

The contour plot in Fig. 6 shows that the higher growth variable (plant height) and marketable yield (fresh shoot weight) were obtained with the higher water hyacinth percentage than coconut coir. Based on the overlay contour plot and 3D surface plot, the optimum composition of BDM for the growth and marketable yield was obtained at 40-70% water hyacinth and 0-20% coconut coir (Figs. 6 and 7).

Based on the response surface analysis, the D value of the optimum and tested BDM compositions that is close to 1 imply that compositions appear to accomplish favorable results for all variables as a whole (Minitab Inc., 2014). Generally, regarding individual desirability (D) value from the tested BDM compositions, the effective composition to maximize the number of leaves and stem diameter ranged from 0.60668-0.88254), while the fresh shoot weight and plant height ranged from 0.57272-0.77523. Based on overlay contour plot

Table 4: Response optimizer of BDM compositions on fresh shoot weight, plant height, number of leaves and stem diameter

Treatment (%Water Hyacinth: %Coconut Coir)	Composite desirability (D)	Desirability (d)			
		Fresh shoot weight	Plant height	Number of leaves	Stem diameter
Optimum (56.43:0)	0.962	0.957	0.895	1.000	1.000
MO1 (80:20)	0.750	0.671	0.728	0.757	0.855
MO2 (70:30)	0.807	0.732	0.774	0.846	0.883
MO3 (60:40)	0.804	0.736	0.775	0.861	0.850
MO4 (50:50)	0.742	0.683	0.733	0.800	0.759
MO5 (40:60)	0.621	0.573	0.646	0.663	0.607

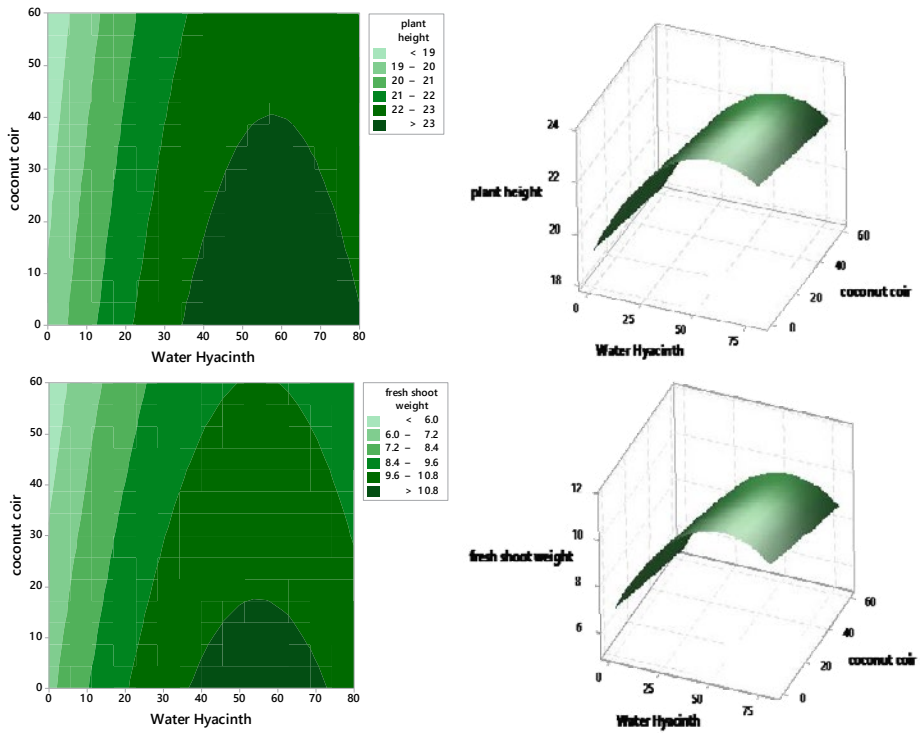

Fig. 6: Contour and surface plots showing the effects of BDM compositions (percentage of water hyacinth and coconut coir) on plant height (top) and fresh shoot weight (bottom) of horenso

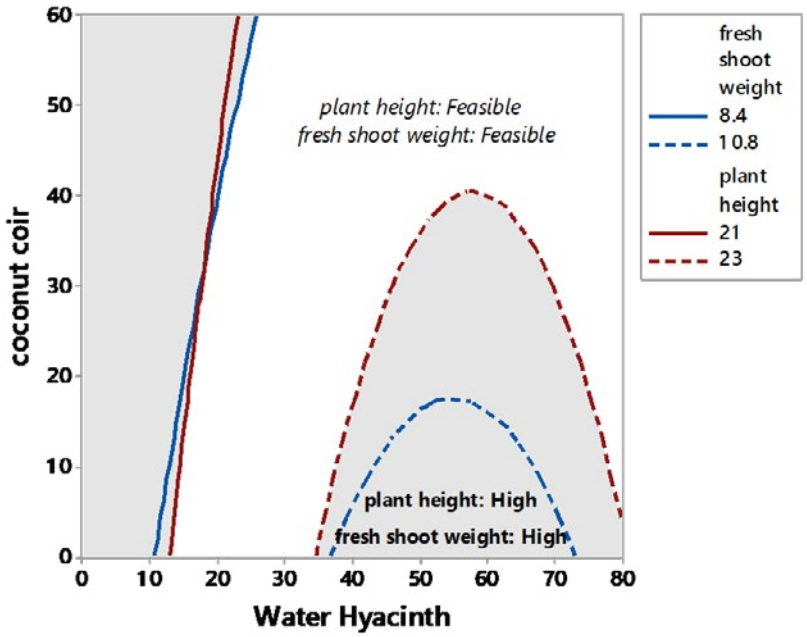

Fig. 7: Overlay countour plot showing the effects of BDM compositions (percentage of water hyacinth and coconut coir) on plant height (top) and fresh shoot weight (bottom) of horenso

and 3D surface plot, the optimum composition of BDM for the growth and marketable yield was obtained at 40-70% water hyacinth and 0-20% coconut coir that was similar to MO2 treatment (70% water hyacinth and 30% coconut coir) with the highest D value compared to the other BDM compositions. Although there was no significant difference in growth and yield of horenso among the differing BDM compositions in general, this optimum composition of BDM can be used as a consideration in the future BDM formulation

CONCLUSION

This study investigated biodegradable mulch composition as microclimate modification effort to combat climate change and to improve the growth and marketable yield of horenso, which may have contributions on other short-cycle crop cultivation. Organic mulch provides a favorable environment for crops and adds nutrients to the soil but its stock is limited due to seasonal and spatial availability and cannot be stored for a long time. On the other hand, plastic mulch is practically easy to use, but less environmentally friendly and expensive disposal cost. Commercial biodegradable plastic mulch is made from expensive raw materials and requires sophisticated production technology. In this study, we attempt to produce biodegradable mulch with abundant and low-cost raw materials using simple technology. The Various tested BDM compositions in this research have contributed a number of modifications on the microclimate by decreasing 1-2°C of soil temperature and maintaining soil moisture within the range of 63-84%. These properties support the adaption effort to combat climate change. High and stable soil humidity indicates the sufficient water availability in the soil for plant growth and development. The optimum composition of the mulch for supporting growth and marketable yield of horenso were obtained with the higher water hyacinth percentage than coconut coir. The optimum composition of BDM for the growth and marketable yield was obtained at 40-70% water hyacinth and 0-20% coconut coir based on the overlay contour plot and 3D surface plot. Referring to the response optimizer analysis with growth and marketable yield as responses, the optimum biodegradable mulch composition was obtained from MO2 treatment (70% water hyacinth and 30% coconut coir) with the highest composite desirability value (D) compared to the other biodegradable mulch compositions. Although there was no significant difference in the growth and yield of horenso among the differing BDM compositions, the BDM composition treatments resulted in significantly higher value than the control (without mulch). The BDM composition treatments could increase fresh shoot weight around 38-55%, fresh root weight for about 55-94%, and dry shoot weight approximately by 1.6-2.8 times compared to the control (without mulch). This finding emphasized that all BDM compositions tested in this current research can be used as mulch in horenso (Spinacia oleracea L.) cultivation. Further research was needed to adapt BDM compositions on other short-cycle crops and other horticulture crops. The long term use of biodegradable mulch in horticulture crops cultivation is not only expected to help crops deal with climate change, but also improve the soil health. Biodegradable mulch is one of the practical aspects to achieve sustainable agriculture that focuses on producing long term crops while having minimal negative impacts on the environment.

AUTHOR CONTRIBUTIONS

A. Iriany contributed in conceptualization, designed methodology, supervision, and writing-original draft. F. Hasanah performed data analysis and interpretation, literature review, and writing-original draft. D. Roeswitawati contributed in supervision. M.F. Bela performed experiments and investigation.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

$\propto$	Level of significance
%	Percent
°C	Centigrade or degree Celcius
µL/L	microlitre per litre
µmol/m^2	micromoles per square metre
ANOVA	Analysis of variance
BDM	Biodegradable mulch
C	Carbon
cm	Centrimetre
cm^2	Square centimetre
CO_2	Carbon dioxide
D	Composite desirability
d	Desirability
DAP	Days after planting
FAO	Food and Agriculture Organization of the United Nations
g	Gram
HSD	Honestly significant difference
kg/ha/week	Kilogram per hectare per week
kg/m^2	Kilogram per square metre
mm	Milimetre
mm per year	Milimetre per year
MO	Control or without mulch (treatment code)
MO1	Biodegradable mulch made of 80% water hyacinth and 20% coconut coir (treatment code)
MO2	Biodegradable mulch made of 70% water hyacinth and 30% coconut coir (treatment code)
MO3	Biodegradable mulch made of 60% water hyacinth and 40% coconut coir (treatment code)
MO4	Biodegradable mulch made of 50% water hyacinth and 50% coconut coir (treatment code)
MO5	Biodegradable mulch made of 40% water hyacinth and 60% coconut coir (treatment code)
mol/mol	mole per mole
P-value	Probability value
r	Pearson correlation coefficient
RCBD	Randomized complete block design
RSM	Response surface method
RuBP	Ribulose 1,5-bisphosphate
SM_{mor}	Soil moisture in the morning
SM_{noon}	Soil moisture in the noon
SOC	Soil organic carbon
SOM	Soil organic matter
T_{max}	Maximum soil temperature
T_{min}	Minimum soil temperature
USDA	United States Department of Agriculture
WAP	Weeks after planting

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ORIGINAL RESEARCH PAPER

Dıscrete-tıme dynamıc water qualıty ındex model ın coastal water

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ABSTRACT

BACKGROUND AND OBJECTIVES: It is important to develop dynamic water quality index software that reflected accurately the state of enclosed coastal water quality. This study explored water quality index model software including the third-order and daily based discrete-time transfer function in Simulink-MATLAB environment to predict the past and future water quality index changes versus discrete-time by using the data measured approximately once a month.

METHODS: A modelling software for daily based discrete-time water quality index was developed to evaluate the pollution level in enclosed coastal water bodies affected by marinas. Measurements were done at three different stations near marina entrances in Bucak, Kaş, and Fethiye Bays located at the south western Mediterranean coast of Turkey. The computed water quality index values and the sampled indicators data defined in terms of the deviation variables were used to identify the proposed third-order transfer function parameters. The proposed software is applicable for past and future estimates, where inputs may include some missing measurements. The input data are interpolated to estimate daily based inputs by using the developed model in the Simulink-MATLAB environment. For model verifications, monthly measured water quality parameters are used.

FINDINGS: The software including the daily based discrete-time transfer function and the input sources was successfully applied to predict past and future water quality index changes with 4.2 percent, 4.3 percent, and 7.1 percent of the absolute maximum errors respectively in Fethiye, Kaş, and Bucak stations. In three stations studied, seasonal comparison of the enclosed coastal water quality showed that the quality in winter (72±2) is lower than the one (82±8) in other seasons. The past and future daily predictions of water quality index changes versus discrete-time were realized successfully by using the proposed software and the data measured approximately once a month.

CONCLUSION: By determining similar transfer functions and selecting some adequate indicators, the software proposed can be adapted for quality assessment in other enclosed water bodies

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INTRODUCTION

The protection of natural water systems is essential due to the continuous need for water in societies (Zhang *et al*., 2012). In the long term, it is possible to protect the natural water ecosystem by reducing pollutant and nutrient inputs (Loucks and Jia, 2012; Capella *et al*., 2013). The nutritional characteristics of different coastal environments, such as estuaries or bays, can be followed comparatively with the help of a selected suitable body of water influenced by various environmental factors (Liu *et al*., 2019; Khaton *et al*., 2017; Simboura *et al*., 2016; Campos *et al*., 2013). The coastal waters, which are affected by river discharges, aquaculture, and some other activities in nearby terrestrial and marine areas, hold an important place today (Pavlidou *et al*., 2015; Lohe *et al*., 2015; Aydinol *et al*., 2012; Karbassi and Pazoki, 2015). Monitoring with the water quality parameters selected in terms of some life forms, and human use shows how industrial and urban wastes pollute the enclosed water bodies (Cebe and Balas, 2016; Pham Phu *et al*., 2018). There are multiple linear regression models developed for bacterial pathogen indicators selected on two beaches on the same coastline showing similar responses to the precipitation effect. However, it is proper to use the indicators and data specific to their locations for beaches located in different areas with different characteristics (He *et al*., 2019; Rees *et al*., 1998). As coastal waters, which are vital for ecosystems, can react very complexly due to environmental conditions, it is crucial to understand how the system in water bodies works and how the variables change those (Hapoğlu *et al*., 2018). A proper and costly tool using satellite ocean color resolutions for marine water quality online monitoring is reported (Farrugia *et al*., 2016). The technique of mapping together the water quality index (WQI) and geographic information system(GIS) data is a simple and reliable tool for determining healthy and polluted areas in coastal water monitoring (Jha *et al*., 2015). There are some studies on the selection of appropriate water quality indices to minimize uncertainty and limiting effects that are needed to classify ecosystem-specific waters for a long time (Rangetti *et al*., 2015; Liou *et al*., 2004)). Many water parameters are monitored by considering the specific target values and mandatory values according to the water quality classes in official regulations (Regulation for the Surface Water Quality, 2016; Regulation for the Water Pollution Control, 2004). Water quality indices (WQIs) calculated using selected parameters and weighting factors provide a tool to monitor and compare the quality of the water system that changes over time (Sargaonkar and Deshpan, 2003; Boyaci et al., 2007; Karakaya and Evrendilek, 2010; Cude, 2001). The use of the area and sources of water determine mostly the parameter weights (Sutadian *et al*., 2017). A region-specific methodological approach has been developed and proposed for similar water bodies to evaluate coastal water quality in recreational areas quickly and to improve monitoring protocols and to test coastal water quality management plans. In these evaluations, a formula approach was made that expresses the sum of the relative weights of each selected variable (Azis *et al*. 2018). The probability of contamination in these ambient water bodies is very high due to the intensive social and vital activities in enclosed coastal waters. WQI approaches are used to evaluate and to compare water quality in different selected coastal water bodies (Nguyen and Sevando, 2019). In the present work, to develop dynamic WQI model using the Simulink-MATLAB environment for the coastal waters was aimed. This discrete-time model is explored for dynamic WQI estimation. The most appropriate model parameter values are calculated using the Bierman (1976) algorithm in the MATLAB environment. Experimental data-based discrete computational points have verified the dynamic model estimates. A WQI model software including the third order and daily based discrete-time transfer function was developed in the Simulink-MATLAB environment. The data obtained for the period of 20 March 2016 to 24 February 2017 were used to identify the transfer function parameters. In the previously published work, areal and temporal comparative analysis and monitoring and evaluation of coastal water quality parameters have been carried out at three stations near marina entrances in Bucak and Kaş Bays (2013-2014), and in Fethiye Bay (2016-2017) located at the south western Mediterranean coast of Turkey (Cebe and Balas, 2016; Yıldırım and Balas, 2019).

MATERIALS AND METHOD

Study area and water quality monitoring stations

Table 1 lists the characteristics of representative stations, namely KM (Kaş Marina), BM (Bucak Marina), and FM (Fethiye Marina), selected for

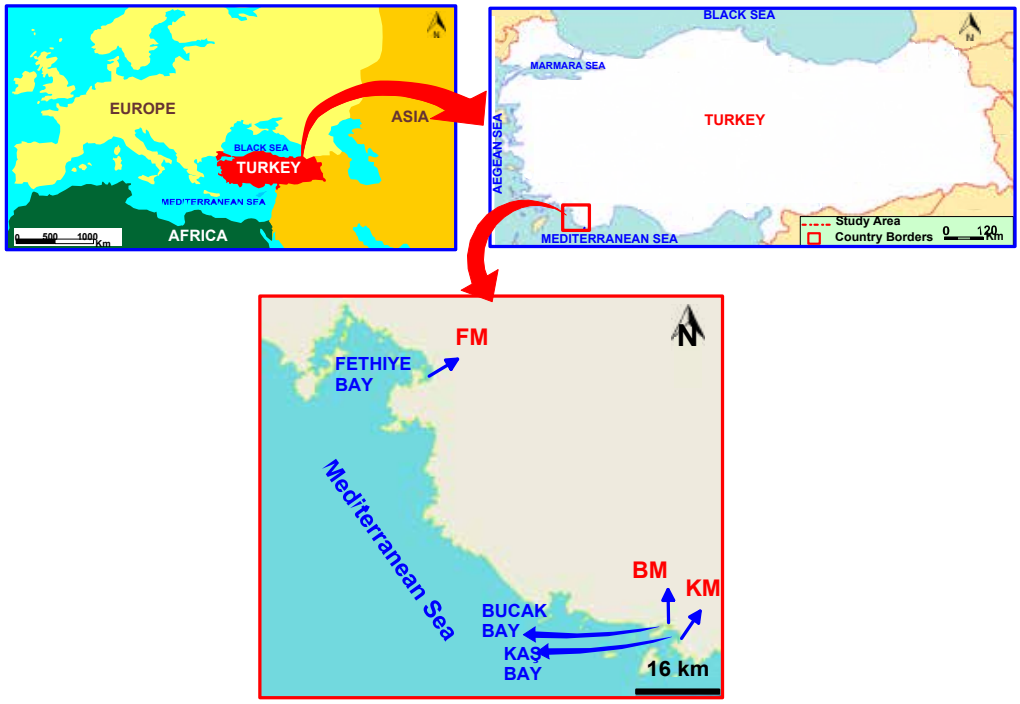

Fig. 1: Geographic location of the study area and measurement stations FM in Fethiye Bay, BM in Bucak Bay and KM in Kaş Bay at the south western Mediterranean coast of Turkey

Table 1: Water depths and coordinates of sampling points (Hapoğlu *et al.,* 2018; Yıldırım and Balas, 2019)

Station	KM	BM	FM
Latitute	36º 11.726′	36º 12.209′	36º 37.680′
Longitute	29º 38.582′	29º 37.430′	29º 6.153′
Water depth	80 m	30 m	15.3 m

the water quality assessment of the receiving environments near marina entrances shown in Fig. 1. The data obtained monthly from these stations are used for WQI calculator in MATLAB environment. The BM station in Bucak Bay, the KM station in Kaş Bay and the FM station in Fethiye Bay represent receiving coastal waters near marina entrances, and sampling from marine waters has been carried out according to TS ISO 5667-9 standard (Yıldırım and Balas, 2019). The main physical and biochemical coastal water quality parameters at the stations are measured from samples taken at -0.5 m below from the water surface. Analysis of parameters has been carried out following Turkish Standards (Yıldırım and Balas, 2019).

Water quality indices

A lot of WQIs such as National Sanitation Foundation Water Quality Index (NSFWQI), Canadian Council of Ministers of the Environment (CCMEWQI) etc. have been formulated (Lumb *et al.,* 2011). Among them, the merits and demerits of NSFWQI, CCMEWQI, Oregon WQI and Weight Arithmetic WQI methods are compared (Tyagi *et al.*,2013). Search for adopted WQIs with little modifications is still going on in different countries. In this study, the known WQI formula based on three different means has been used. Weighted Mean Water Quality Index (WM - $WQI_{x\,=\,1\text{-}n}$) is given in Eq. 1. The weight factors (Wx) of the parameters are used as constant values. Unweighted Mean Water Quality Index (UM - $WQI_{x\,=\,1\text{-}n}$) is formulated as in Eq. 2 (Katyal, 2011) Unweighted Harmonic Square Mean Water Quality Index (UHSM - $WQI_{x\,=\,1\text{-}n}$) is presented in Eq. 3 (Rangetti *et al.*, 2015). Here, the number of parameters chosen

to calculate WQI values is n. The symbol Q_x indicates the quality values of the parameters indicated by the subscript x. By assigning ten numbers to the x symbol, total coliform (TC) (x = 0), fecal coliform (FC) (x = 1), total suspended solids (TSS) (x = 2), nitrate (NO_3) (x = 3), turbidity (x = 4), pH (x = 5), temperature difference (ΔT) (x = 6), percent saturated dissolved oxygen (%(sat)DO) (x = 7), biochemical oxygen demand (BOD) (x = 8), total phosphate (TP) (x = 9) indicators have been obtained. WQIs with high number of parameters and WQIs with only three parameters can be applied to evaluate the overall variation of water quality. In these calculations, TC can be used as bacterial indicator (Pesce *et al.,* 2000). By considering previously published work on coastal water parameters in the same locations (Cebe and Balas, 2016; Hapoğlu *et al.,* 2018; Yıldırım and Balas, 2019), the 10 parameters mentioned above were selected for this study. Hapoğlu *et al.* (2018) reported succesfull usage of WQI with x=1,6,7 in Kaş Bay by realizing statistical analysis of the water quality parameters and the indices with the different number of parameters. After checking the indices given below with the different number of parameters such as x=1-7, x=1-9, x=0,2-9, x=1,6,7, x=0,6,7. Three parameters, x=0,6,7, are chosen to developed dynamic model in this work. As a bacterial indicator, FC or TC can be chosen. Because of larger amount existance in the region, TC are prefered as a model input.

$$\text{WM-WQI}_{x=1\text{-}n} = \frac{\sum_{x=1}^{n} Q_x W_x}{\sum_{x=1}^{n} W_x} \quad (1)$$

$$\text{UM-WQI}_{x=1\text{-}n} = \frac{\left[\sum_{x=1}^{n} Q_x\right]}{n} \quad (2)$$

$$\text{UHSM-WQI}_{x=1\text{-}n} = \left[\frac{n}{\sum_{i=1}^{n} Q_x^{-2}}\right]^{0.5} \quad (3)$$

The non-dimensional quality values are provided for each parameter by using interpolation with the developed software in MATLAB environment (Hapoğlu *et al.,* 2018). From this software, BOD, TP and TC qualities are also obtained by implementing the piecewise cubic Hermite interpolation. Figs. 2 and 3 show the BOD quality and TP quality curves, respectively. The curve linking the overall bacterial quality to the TC indicator value is given in Fig. 4, considering the close relationship between the FC and TC indicators. This curve is useful, especially if the FC bacteria number is low.

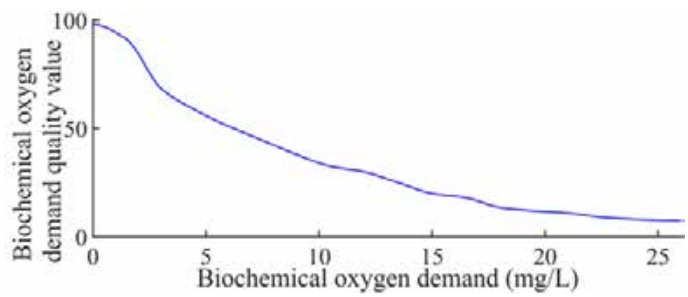

Fig. 2: The relationship between biochemical oxygen demand and its quality value

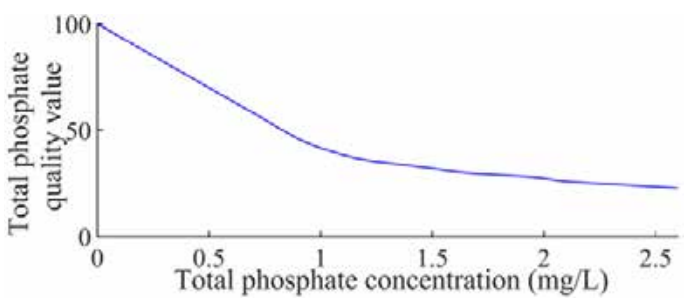

Fig. 3: The relationship between total phosphate and its quality value

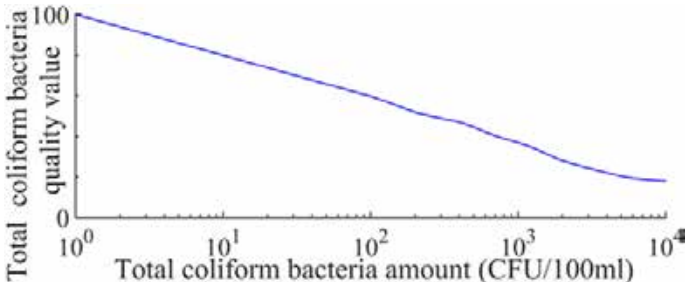

Fig. 4: The relationship between total coliform bacteria amount and its quality value

In the known WQI formulas, the selection of parameters to be used as an indicator is important since the quality value of some parameters is high so that the calculated index value can be high (Hapoğlu *et al*., 2018). Besides, an indicator with a high pollution effect can create a sensitivity difference between different WQI formulas. In this study, known WQI formulas were developed based on the minimum norm with the technique described below to increase the sensitivity between formulas. Weighted mean water quality index (WM-WQI-MN) based on minimum norm, unweighted mean water quality index based on the minimum norm (UM - WQI-MN) and unweighted harmonic square mean water quality index based on the minimum norm (UHSM-WQI-MN) are calculated with the software prepared in MATLAB environment using calculation steps in Eqs. 4-10. Binary element evaluations defined in Eq. 5 are made between two parameters, such as parameter i and parameter j for the matrix given in Eq. 4. These binary element calculations are made between two parameters, such as parameter i and parameter j for matrices (A_t, B_t, C_t) to be generated based on each WQI formula. These matrices are calculated from the following Eqs. (4-9) for each individual sampling step (t = 1,2,…, m). Formulas in Eqs. 1-3 (WM-WQI$_{x\,=\,1\text{-}n}$, UM-WQI$_{x\,=\,1\text{-}n}$, UHSM-WQI$_{x\,=\,1\text{-}n}$) are developed based on the minimum norm (MN) as given in Eqs. 11 to 13 by the technique described above.

$$A_t=\begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \quad (4)$$

$$a_{ij}=\frac{\left\{W_{x=i}\left(\frac{Q_{x=i}}{100}\right)+W_{x=j}\left(\frac{Q_{x=j}}{100}\right)\right\}}{\left(W_{x=i}+W_{x=j}\right)} \quad (5)$$

$$B_t=\begin{bmatrix} b_{11} & \cdots & b_{1j} \\ \vdots & \ddots & \vdots \\ b_{i1} & \cdots & b_{ij} \end{bmatrix} \quad (6)$$

$$b_{ij}=\frac{\left(Q_{x=i}+Q_{x=j}\right)}{200} \quad (7)$$

$$C_t=\begin{bmatrix} c_{11} & \cdots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \cdots & c_{ij} \end{bmatrix} \quad (8)$$

$$c_{ij}=\left(\frac{2}{\left(\frac{Q_{x=i}}{100}\right)^{-2}+\left(\frac{Q_{x=j}}{100}\right)^{-2}}\right)^{0.5} \quad (9)$$

WQI matrices (At, Bt, Ct) with different binary indicator elements were used to obtain WQI values on the basis of the MN for each t, as in the A_t example shown in Eq. 10. In MATLAB environment, the MN is calculated with the software developed as the matrix two norm ($||At||_2$) ||, which provides the smallest size measurement (Chapra, 2012). The E_{max} value in Eq. 10 is the largest eigenvalue ($[A_t]^T[A_t]$).

$$A_{t2}=\left(E_{max}\right)^{0.5} \quad (10)$$

In this study, three different WQI calculations based on the MN for each t were performed using Eqs. 11 to 13.

$$\text{WM-WQI-MN}=\left(\frac{A_{t2}*100}{n}\right) \quad (11)$$

$$\text{UM-WQI-MN}=\left(\frac{B_{t2}*100}{n}\right) \quad (12)$$

$$\text{UHSM-WQI-MN}=\left(\frac{C_{t2}*100}{n}\right) \quad (13)$$

To evaluate WQIs from the six formulas mentioned above, the non-dimensional quality values and weights are obtained from the previously developed software in MATLAB environment (Hapoğlu *et al*., 2018). NSFWQI Rating (excellent (91-100), good (71-90), medium (51-70), bad (26-50), very bad (0-25) reported by Tyagi *et al.* (2013) is used to rank the six WQI formulas.

Discrete time transfer function for water quality index estimation

TC, temperature, and DO monthly sampled indicator data and WQI values calculated with the selected formula (Eq. 13) are used for daily data generation using the zero-order hold element. The proposed transfer function parameters with the daily data generated are calculated using the Bierman (1976) algorithm. Input and output variables of the proposed transfer function are defined in terms of the deviation variable. Here [(UHSM-WQI-MN)-(UHSM-WQI-MN)$_b$], [ΔT-ΔT_b], [%(sat)DO-%(sat) DO$_b$], and [TC-TCb] values are defined as the output variable (OV), the first input variable (IV1), the second input variable (IV2), and the third input variable (IV3), respectively. The third-order transfer function with three inputs and one output variable is given in Eq. 14. The dynamics of the stations dictates the sampling time required. The sampling time of this transfer function is chosen as one day. Thus the model requires inputs data at every sampling time. To obtain output behaviour versus time, necessary inputs are provided by using repeating sequence interpolation technique.

$$\begin{aligned}\text{OV}=&\frac{0{,}00053258z^3-0{,}0014z^2}{z^3-0{,}9990z^2+0{,}0026z-0{,}0059}\text{IV1}\\ &+\frac{-0{,}0854z^3+0{,}1422z^2}{z^3-0{,}9998z^2-0{,}2787z+0{,}4726}\text{IV2}\\ &+\frac{0{,}0040z^3-0{,}0079z^2}{z^3-0{,}9859z^2-0{,}1514z+0{,}2741}\text{IV3}\end{aligned} \quad (14)$$

The model (Eq. 14) calibration is achieved in MATLAB environment by using the recursive algorithm (Bierman, 1976) and a random sequence input produced based on experimental data obtained monthly from FM station with zero-order hold element. This input is utilised as a forcing function in order to determine the transfer function parameters. No previous knowledge of the model parameters was assumed so that the initial set of parameter estimates is fixed equal to zero with large initial values used for the covariance matrix diagonal elements. The parameter evaluation is performed recursively using the Bierman (1976) update algorithm in MATLAB environment. For the model verification, the experimental data obtained monthly from FM station are compared with the model output (Fig. 10). For the last stage , BM and KM are selected far from FM to illustrate model applicability. The evaluation stage is executed by comparing the simulated WQI values in different stations in the different time domain with the WQI values evaluated from experimental measurements (Fig. 11). In this study, a model for WQI, which includes daily based discrete-time transfer function given in Eq. 14 in Simulink-MATLAB environment, has been developed. In case the daily input data is missing, the developed model can generate the input data using the repeating sequence interpolation technique and perform estimates of WQI that can be defined as the past and the future according to the specified initial date indicated by sub-index b.

RESULTS AND DISCUSSION

The enclosed coastal WQI assessment has been performed at three stations near marina entrances in Bucak, Kaş, and Fethiye Bays on the Mediterranean coast of Turkey by calculations with monthly intervals using WM-WQI, UM-WQI, UHSM-WQI formulas. WQI values are calculated by using different formulas with seven indicators from x = 1 to 7 for the BM station in Bucak Bay, as shown in Fig. 5. In winter, the results of UHSM-WQI create more fluctuations than the results of WM-WQI and UM-WQI. An evaluation comes out that these fluctuations might be due to the sensitivity to load effects of fecal coliform concentration. There has been a significant relationship between the T and DO (r=-0.8480, p=8.7995E-6), DO and TC (r=0.7422, p=4.2062E-4), TC and FC (r=0.5100, p=0.0306) data pairs. However, there is no significant relationship between DO-FC data pairs (r = 0.4402, p = 0.0675). For very close Kaş Bay region, previously reported DO-FC data pairs (r=0.6980, p= 0.0001) indicates significant

relation (Hapoğlu *et al*., 2018). The ratios of FC at BM station to FC at KM station are 0.459 (21.12.2013) and 1.335 (8.2.2014). The ratios of TC at BM station to TC at KM station are evaluated as 1.123 (21.12.2013) and 1.158 (8.2.2014). This result shows that there are direct FC discharges in the environment. Fig. 5 shows WM-WQI-MN, UM-WQI-MN, UHSM-WQI-MN values calculated with the same seven parameters. These WQI formulas are developed based on the MN with matrix elements based on WQI values calculated on indicator pairs quality values (Eqs.11-13). These curves, based on the MN, which change more closely with each other, show high sensitivity considering the relationship between other traditional formulas. UHSM-WQI-MN values constitute the lower limit among the curves based on the MN, while the WM-WQI results follow a path between the UM-WQI and the UHSM-WQI curves. In index formula calculations that use a large number of indicators, some quality parameters that indicate a low level of pollution may mask the emergence of problems associated with changes in other quality parameters (Hapoğlu *et al*., 2018). The evaluation to solve this problem is that it would be appropriate to use fewer significant indicator parameter groups in the light of monitoring studies with WM-WQI calculated with three parameters (x = 1, 6, 7) in Kaş enclosed coastal water body containing many station data (Hapoğlu *et al*., 2018). This selection, which is proposed over the water body without excessive pollutant input, has been compared in this study for BM, KM, and FM stations near marina entrances.

All WQI formulas calculated using seven indicators for BM station selected in Bucak Bay shown in Fig. 5 are recalculated by using only FC (x = 1), ΔT (x = 6) and %(sat)DO (x = 7) parameters and given in Fig. 6. As a result of the comparison of these index curves, UHSM-WQI-MN values calculated with a small

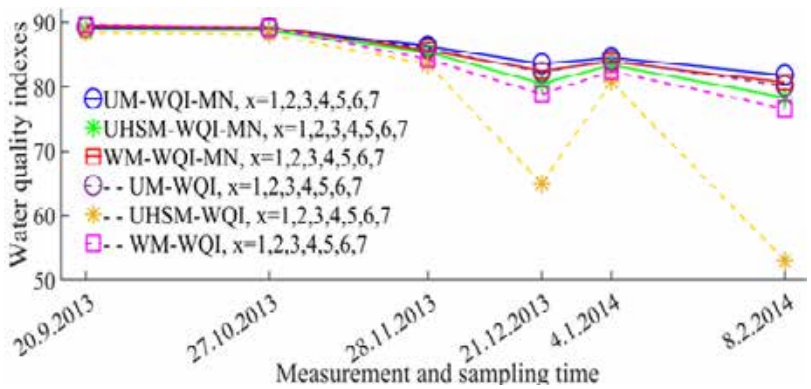

Fig. 5: Change of water quality indices with seven parameters with respect to time for station BM

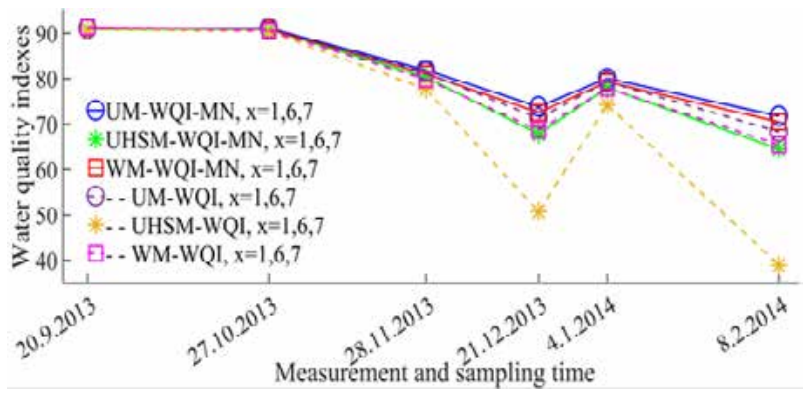

Fig. 6: Change of water quality indices with three parameters with respect to time for station BM

number of selected parameters are found suitable for monitoring.

KM station selected in Kaş Bay has shown a similar change in WQI with the BM Station compared to the FM station. It is possible to understand this similarity from the comparison of WM-WQI-MN, UM-WQI-MN, UHSM-WQI-MN values calculated with three indicators (x = 1,6,7) as shown in Fig. 7 and the changes given in Fig. 6. There is a significant seasonal decrease from WQI values, which is 80-95 in autumn to 70-80 index values in winter. At FM station in winter, UHSM-WQI-MN values monthly calculated with three indicators (x = 1,6,7) were 73.84, 78.23, and 65.82. UHSM-WQI-MN values with three indicators (x = 0,6,7) were also monthly calculated for winter as 73.25 , 68.95, and 68.38. By comparing 73.84 in December and 78.23 in January, the low amount of fecal coliforms pointed out at station FM is sufficient to cover up the seasonal index decrease at FM station in Fethiye Bay. As a result of the statistical analysis performed with the measurements taken from the station FM, a significant relationship ($p < 0.05$) has been detected between the T and DO ($r=-0.8845$, $p=0.0082$) data pair. The lack of a significant relationship between the data pairs of FC measurements with DO($r=0.6143$, $p=0.1422$), pH ($r=0.0718$, $p=0.8784$) and T ($r=-0.7022$, $p=0.0786$) supports the direct fecal coliform entries that cover up WQI. Fig. 8 shows the annual changes in WQI-MN, UM-WQI-MN, UHSM-WQI-MN values calculated monthly with three (x=1,6,7) and nine (x=1-9) parameters using FC as the bacterial indicator for the FM station. The use of FC as a bacterial indicator in the FM station with high direct input effects has been examined. It has been evaluated that these values, which are much less than TC amounts, are not sufficient for the determination of the sensitive dimensionless bacterial indicator quality value. This assessment has been supported by monitoring that the fall and

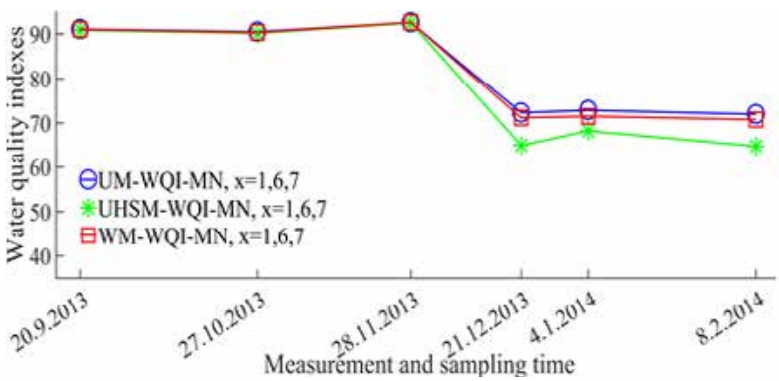

Fig. 7: Change of water quality indices with three parameters with respect to time for station KM)

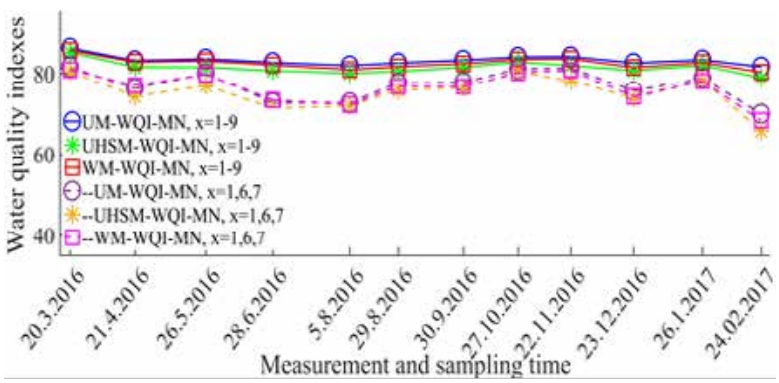

Fig. 8: Change of water quality indices with three and nine parameters with respect to time for station FM

winter seasonal changes seen in FM station did not show a significant decrease as seen in WQI in BM and KM stations (Figs 6 and 7).

The changes of WQI-MN, UM-WQI-MN, UHSM-WQI-MN values with three (x = 0,6,7), and nine (x = 0, 2-9) parameters using TC bacteria measurements in the computations of dimensionless bacterial quality value (Fig. 4) for Station FM with time is shown in Fig. 9. UHSM-WQI-MN, which generates lower limit values in quality monitoring with three parameters (x = 0,6,7), has been evaluated that quality monitoring, estimation, and comparison can be made in similar stations near marina entrances.

Dynamic WQI (UHSM-WQI-MN) has been created in the Simulink-MATLAB environment, which uses interpolation in the input data defined with a daily based discrete-time transfer function (Eq. 14) as monitoring, estimation and comparison tool. The model parameter estimation used in the software has been carried out with monthly measurements from the FM station, and daily random input values produced using the zero-order hold element. The changes in daily UHSM-WQI-MN values for FM station estimated by this software are given in Fig. 10. TC_b, DT_b, $\%(sat)DO_b$, and $(UHSM\text{-}WQI\text{-}MN)_b$ values calculated by the measurements dated 29 August 2019 were used as the initial values in obtaining output indicated by a line. The daily UHSM-WQI-MN software outputs obtained for backward and forward of the selected initial date are compared with WQI data calculated from monthly measurements (WQI-MN, UM-WQI-MN, UHSM-WQI-MN) displayed with symbols. Based on these comparisons, software predictions have been found very successful for station FM. The daily input data is provided by using the Simulink library with the repeating sequence interpolation method in the software that uses a daily discrete-time step. The applicability of this

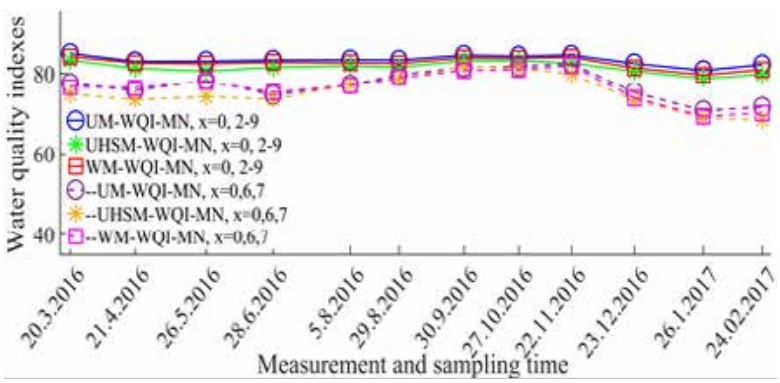

Fig. 9: Change of water quality indices using total coliform as bacterial indicator with three and nine parameters for the station FM with time.

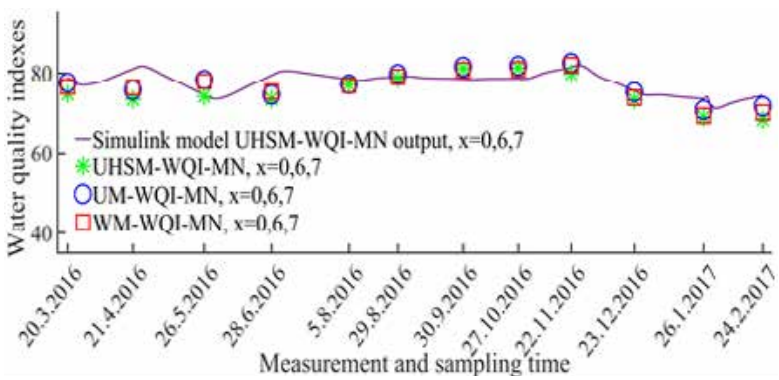

Fig. 10: Water quality index output from model with three input variables for station FM

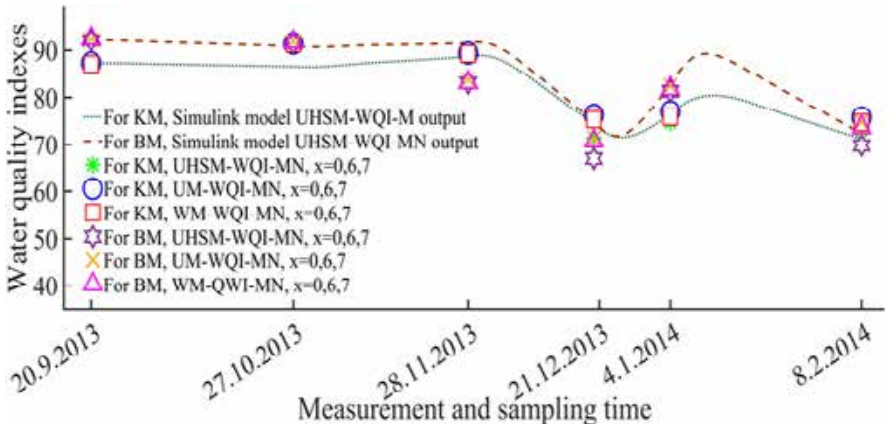

Fig. 11: Water quality index output from model with three input variables for stations KM and BM

Table 2: A comparative water quality assessment at FM, BM and KM stations

Season	Station FM Seasonal evaluation for 20.3.2016-24.2.2017 with montly UHSM-WQI-MN(x=0,6,7)	Station BM Seasonal evaluation for 20.9.2013-08.2.2014 with montly UHSM-WQI-MN(x=0,6,7)	Station KM Seasonal evaluation for 20.9.2013 -08.2.2014 with montly UHSM-WQI-MN (x=0,6,7)
Spring	Good ([75+73+74]/3=74)		
Summer	Good ([74+77+79]/3=76,7)		
Autumn	Good ([81+81+80]/3=80,7)	Good ([92+92+83]/3=89	Good ([87+91+89]/3=89)
Winter	Medium-Good ([73+69+68]/3=70)	Good ([70+81+70]/3=73,7)	Good ([71+75+71]/3=72,3)

software as a follow-up, estimation, and comparison tool has been investigated for nearby similar stations, BM, and KM (Fig. 11). Software outputs shown with different dashed lines for the station KM and BM were obtained using TC_b, DT_b, $\%(sat)DO_b$ and $(UHSM\text{-}WQI\text{-}MN)_b$ values initially calculated by the measurements dated 20 September 2013. The software results shown in Fig. 11 have been found successful in the five-month forecast and follow-up from the initial value. The software developed has been successfully applied for the comparison of the WQI changes in the same time interval for station KM and BM. UHSM-WQI-MN data calculated from monthly measurements are given in Table 2 for three similar stations in the enclosed coastal areas shown in Fig. 1. Although the general quality evaluation is good, it has been calculated that the WQI values from autumn to winter decreased by 13.2% for FM station, 17.2% for BM station, and 18.7% for KM station. When resultant curves of the software given in Figs. 10 and 11 are examined for the same three stations, the water quality has been classified as good with the observation of a slight decrease from autumn to winter.

CONCLUSION

An enclosed water quality assessment of three different stations was monthly performed to investigate the usage of the conventional and the proposed generalized formulas of WQIs. The absolute maximum discrepancy among the conventional formulas used was detected as 30 percent. The discrepancy among the proposed formulas was found as 7.1 percent. The conventional WQIs with much noisier index curves may be ill-suited with respect to constant or equal weighting

factors utilization, number of parameters chosen and external disturbances availability. Accordingly the application of a generalization technique based upon MN was proposed to maintain the desired robustness and the smoothness of the index curves versus discrete sampling time. For station BM, among both three conventional WQIs with x=1-7 and three proposed WQIs based on MN with x=1-7, an absolute maximum discrepancy of 27 percent, and 3 percent were detected respectively (Fig. 5). Besides, among both three conventional WQIs with x=1, 6, 7 and three proposed WQIs based on MN with x=1, 6, 7, an absolute maximum discrepancy of 30 percent, and 7.1 percent were detected respectively (Fig. 6). For station KM, among three proposed WQIs based on MN with x=1, 6, 7, an absolute maximum discrepancy of 7.1 percent was found (Fig. 7). For station FM, among both three proposed WQIs based on MN with 1-9 and three proposed WQIs based on MN with x=1, 6, 7, an absolute maximum discrepancy of 3.1 percent, and 4.6 percent were detected respectively (Fig. 8). Besides, among both three proposed WQIs based on MN with x=0, 2-9 and three proposed WQIs based on MN with x=0, 6, 7, an absolute maximum discrepancy of 3.1 percent, and 4.6 percent were determined respectively (Fig. 9). The UHSM-WQI-MN proposed among other formulas was found sensitive enough by considering performance comparison with the usage of various numbers of indicators. The computed WQI values and the sampled indicators data of TC, T, DO in the form of deviation were used to identify the proposed third order transfer function parameters. The software including the daily based discrete time transfer function and the input sources which the daily based indicators data were determined by using interpolation technique among the monthly sampled inputs was proposed and successfully applied to predict past and future water quality index changes versus time. The maximum absolute errors between the WQI calculated from experimental measurements and the simulated WQI from the software developed are found as 4.2 percent, 4.3 percent, and 7.1 percent respectively in Fethiye, Kaş, and Bucak stations. For the quality prediction and comparison, the software proposed can be adapted to other enclosed coastal water. Thus it may provide an effective tool in the comparable enclosed coastal water bodies. In this study, the model described above has been developed in the Simulink-MATLAB environment and proposed as a reliable tool with flexible applicability for coastal water quality index follow-up, prediction, and comparisons. The model has been successfully applied to enclosed coastal water bodies of Bucak, Kaş, and Fethiye Bays having marinas. In software development, a daily discrete-time third-order three inputs, and one output transfer function were found suitable for the region studied. FM station measurements define the parameters of this model. This software has successfully provided the predictions and comparisons of daily changes in UHSM-WQI-MN at the same stations, with the application of newly selected initial dates and different date intervals for the future. This software can be applied for stations with different features in the same region by updating the model parameter identification step with the representative station measurements. This software can be applied to other enclosed coastal water bodies by using the repeatable steps of selecting the appropriate number of indicators and determining the transfer function parameters by using the regional descriptive measurements obtained.

AUTHOR CONTRIBUTIONS

H. Hapoglu developed a model in the Simulink-MATLAB environment, and provided the WQI data, prepared the manuscript text. Ş. Camcioglu provided some non-dimensional quality values in MATLAB environment. B. Ozyurt helped in the literature review and provided some of the remained non-dimensional quality values in MATLAB environment. P. Yıldırım performed the analyses on water quality parameters. L. Balas conducted field measurements and performed coastal water quality evaluations, compilation of the data 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.

ABBREVIATIONS

A_t	Water quality index matrix
$[A_t]^T$	Transpose of the matrix
$\|\| A_t \|\|_2$	The matrix 2 norm
BOD	Biochemical oxygen demand
BM	Bucak Marina
DO	Dissolved oxygen
E_{max}	The largest eigenvalue of ($[A_t]^T[A_t]$).
FC	Fecal coliform
FM	Fethiye Marina
GIS	Geographic information system
KM	Kaş Marina
MATLAB	Software environment developed as a matrix laboratory
MN	Minimum Norm
NO_3	Nitrate
p	Significance value, significant for p <0.05 condition
Qx	Quality value of the parameter indicated by the index x
r	correlation coefficient
T	Temperature -0.5 m depth below the surface
TC	Total coliform bacteria
TC_b	Accepted initial value at a specific sampling date selected for the total coliform
Tref	Reference temperature -10m depth below from the surface
TSS	Total suspended solids
TP	Total phosphate
WQI	Water Quality Index
UHSM-WQI	Unweighted Harmonic Square Mean Water Quality Index
UM-WQI	Unweighted Mean Water Quality Index
WM-WQI	Weighted Mean- Water Quality Index
W_x	Weight factor of the parameter indicated by the index x
%(sat)DO	The ratio of 100 times the DO value to the 100% saturated DO value
$\%(sat)DO_b$	Accepted initial value of % (sat) DO value on a selected sampling date
DT	Difference from reference temperature value (Tr_{ef}) and surface temperature value (T), (Tr_{ef}-T)
DT_b	Accepted initial value at a specific sampling date selected for the temperature difference

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ORIGINAL RESEARCH PAPER

Fuel wastage and pollution due to road toll booth

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ABSTRACT

BACKGROUND AND OBJECTIVES: The study provides an assessment of fuel wastage, particulate matter particles pollution, and noise pollution at three toll booths near district Varanasi, India. The objective of the study is to analyze the effects of vehicle idling conditions on road tolls in terms of pollution and fuel wastage.

METHODS: The study used mathematical formulation on queuing observations for assessment of fuel wastage due to vehicle idling at toll booths. Handheld device HT-9600 Air Particle counter was used for getting the readings of PM2.5 and PM10. SL10 noise meter of Extech Instruments was used for measuring the noise levels at the selected three toll booths of Dafi Toll Booth, Lalanagar Toll Booth, and Mohania Toll Booth.

FINDINGS: The study assessed a greater extent of fuel wastage at all the three toll booths with maximum fuel wastage at Dafi Toll booth due to vehicle idling. In terms of air pollution, severe levels of particulate matter particles were observed over all the three toll booths. The noise levels over the three toll booths were also observed significantly high.

CONCLUSION: The study suggested that serious measures are required to control and regulate toll booths to avoid vehicle idling, which will lead to savings of fuel and air and noise pollution.

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INTRODUCTION

With the rapid growth in population, scarcity of natural resources and environmental degradation have emerged as serious concerns globally. Researchers are putting effort to identify all possible ways to limit the wastage of natural resources and control of environmental pollution. A significant source of natural resource consumption and pollution in the present world is transportation. In the United States itself, around 30 percent of Green House Gases emissions are accountable to the transportation sector only (EPA, 2017). A report from European Environment Agencies states that the transportation sector is liable for more than 13 percent to the total release of air pollutants, and over to that, more than 50 percent of NOx is coming from transport in the European Union (EPA, 2019). In developing countries like India, significant growth of air pollution has been observed due to the growing rate of vehicle transportation (Jason, 2015). Concerns with the transport segment are not limited to air pollution only. The transport segment also offers several other issues related to noise pollution, traffic congestion, augmented travel timings, and natural resources such as fossil fuel consumption. These issues have compelled researchers to find innovative solutions to optimize transportation systems in terms of minimum vehicular pollution, economic feasibility, and operability. Particularly, the road transportation accounts for a major share of fuel consumption as well as pollution emission (Jiménez-Uribe *et al*., 2020). With more vehicles adding up every year in the road system, a rapid rise in fuel economy can be observed. Road transportation is also liable for environmental and health problems in the urban and rural areas linked with the roadways. Prolonged exposure to common vehicular pollutants like PM_{10} and $PM_{2.5}$ can lead to various respirational and cardiovascular issues. On an estimate, particulate matter particle pollution caused 620000 non-natural deaths in India in the year 2010 itself (Surendra, 2016). Another form of pollution that comes with vehicular emissions is noise pollution, and facts show that noise pollution due to traffic is also a severe concern posing adverse environmental and health effects (Espinoza-Arias *et al*., 2019; Singh *et al*., 2020). The excessive traffic on urban roads in cities and highways causes sound pollution, which is triggering hearing ailments in regular traffic commuters (Cai *et al*., 2019). Any effort towards limiting the air and noise pollution and fuel wastage can be an aid in reducing the environmental health concerns and economic burden, especially in developing countries. A reasonable effort for reducing fuel wastage and minimizing vehicular pollution can be automation or removal of road toll booths (toll plazas). Road tolls are employed to generate funds from commuters using highways. These funds are used to incur the development and maintenance costs of the roadways. Tolls do not merely break the flow of traffic but also are a source of fuel and time wastage along with pollutant generation due to vehicle idling. Various incidents happened throughout the world in which highways were in traffic jam conditions for many hours and sometimes stretched for days and weeks, and in many such cases, the reason was inefficient systems at toll plazas, especially the manually operated ones (Deccan Chronicles, 2016; Gorzelany, 2015; You, 2015). In India, a report from Transportation Corporation of India and IIM Kolkata estimated that interruptions at toll plazas and slow pace of heavy freight vehicles had put a cost burden of USD 12 billion per annum on the Indian economy (TCI, 2016). The delays at the toll booths add up the immediate effect to rise in transportation cost and wastage of fuels and also present the severe concerns of air pollution (Lin *et al*., 2020; Wang *et al*., 2020) and noise pollution (Fider *et al*., 2017), which can be avoided with efforts of optimizing the road tolls. One of the groups of people who directly get affected with pollutants and noises are the toll operators and servicemen in manually controlled toll booths. Since an enormous number of vehicles pass every day on tolls, emitting out much of pollutants and noises, toll workers become the victim of exposures causing severe effects on their health. Even limited exposure to diesel exhaust can be a reason for eyes and throat irritations, respiratory ailments, and pains in the chest and leg regions for the ones who are having some heart problems. Prolonged exposures to ultra-fine pollutant particles that are common at toll booths can lead to severe pulmonary health problems and even to DNA damage (Belloc-Santaliestra *et al.*, 2015). Besides the effects of air pollutants, noise pollution at toll booths is also a serious issue (Kim *et al.*, 2016). Many of the past studies have proved road toll booth employees and highway workers are exposed to noise levels, which are perilous to hearing

(Fider *et al.*, 2017; Fiest *et al.*, 2001; Nadya *et al.*, 2010). In relation to the fossil-based fuels, there is an ascending price trend and growth in global demand due to the rapid industrialization and transportation advancements. Following the basic concept of demand and supply, as non-renewable resources become scarcer, the cost to obtain them will continue to rise. Supply for many of these fuels is at risk of ending, and gradually the price will hit a point that end-users will not be able to afford. India, being a developing economy, has also seen a rapid upsurge in the vehicular population in recent years. In the year 1951, the number of vehicles estimated to be around 0.31 Million, which rises to 115 million by the year 2014 (Road Transport Year Book: 2007-09, 2011). By the year 2040, the total vehicular population is forecasted to be around 206 million to 309 million (Tiwari *et al.,* 2013). The rising number of vehicles increased the issue of traffic chaos leading to avoidable vehicle idling, which is a major concern of fuel wastage and pollution. A research estimated that in the national capital of India, a car ran only at 4 kmph for 24% of their travel time and with such rate for a million cars running every day, will account for a total wastage of 0.25 million liters of fuel per day (Goel *et al.*, 2015). Other than the traffic chaos, vehicle idling can often be seen at toll plazas on highways, which accounts for avoidable fuel wastage and pollution. In the presented work, estimation was done for the wastage of fuel due to vehicle idling in the queues at the toll plazas. Various efforts have been put by researchers throughout the globe for assessing the toll booth operations so that delays, as well as pollution and its impacts, can be avoided. Fu and Gu (2017) have given a relationship between traffic flow and the cost-benefit of a trip. They related it with the congestion and pollution externalities with and without the presence of toll booths on a fixed trip between two locations showing the effect of toll plazas on cost per trip and traffic flow. Blanc (1987); Chakroborty *et al.* (2016); Conolly (1984); Edie (1954); Haight (1958); Jaiswal *et al.* (2019a); Jaiswal *et al.* (2019b); Schwartz (1974), and several others have worked on assessing the queuing process at road networks as well as at toll booths and presented optimal queuing models for toll booths and highways. Congestion pricing (Zhang and van Wee, 2012), dynamic road pricing (Chang and Hsueh, 2006), AI-based system (Tan *et al.*, 2017), drivers' adaptation (Heras-Molina *et al.*, 2017) have also been analyzed for toll booth operations with time and environment optimized conditions. In the presented research study, three of the toll booths over Indian National Highways were observed for estimating the traffic flow, fuel consumption, particulate matter particle in the air, and noise levels. This study aimed to analyze the effects of vehicle idling conditions at road tolls to assess the fuel wastage and air and noise pollution at the toll booths. The paper presents an estimated analysis of the data generated for the total annual loss and pollution impact over the environment due to vehicle idling at toll booths on Indian National Highways. This study has been carried out for three toll booths on Indian National Highway 19 (NH-19) nearby district Varanasi in the states of Uttar Pradesh, India. The data was collected for the study in 2017.

MATERIALS AND METHODS

Region of study and data collection

Three of the road toll booths: Lalanagar Toll Plaza (Latitude: 25.267233, Longitude: 82.490525), Dafi Toll Plaza (Latitude: 25.248459, Longitude: 82.994053), and Mohania Toll Plaza (Latitude: 25.188447, Longitude: 83.561507), on Indian National Highways 19 near to district Varanasi were selected to collect the data for analysis over fuel wastage and pollutants. As the three toll booths are near to district Varanasi, the climatic conditions of the toll booths are also according to the city. These toll booths belong to a humid subtropical climate with dry winters, and temperatures ranged from 3°C to 18°C and rainy summers with a temperature higher than 22°C (Nistor *et al.*, 2020). Fig. 1 shows the map of the selected toll booths for observation.

A survey was conducted over the three tolls to identify the peak hours and the off-peak hours of the traffic in a day. For air pollution data, a total of 5 samples each in the peak hours and non-peak hours were taken for 20 days from the period of 10 May 2017 to 14 July 2017. The mean of each day sample was assessed for the level of air pollutants in terms of Particulate Matter $PM_{2.5}$ and PM_{10}. A handheld device, HT-9600 Air Particle Counter, was used to get the readings of $PM_{2.5}$ and PM_{10}. For assessment of noise levels at the selected toll booths, handheld sound meter device SL10 from Extech Instruments was used. Five samples in peak hours and five samples in off-peak hours for an interval of 10 minutes were

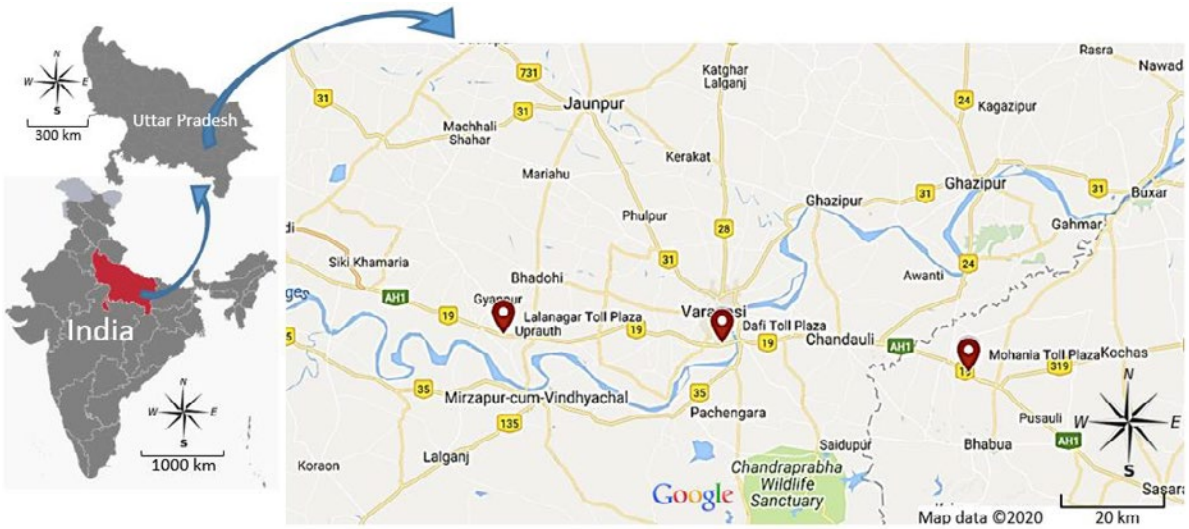

Fig. 1: Geographic location of the study area along with the selected road toll booths for data and sample collection

collected for 20 days during a period of 10 May 2017 to 14 July 2017; overall, the three stated road toll plazas and its mean was assessed over the permissible limits. Descriptive statistics were used for the analysis of $PM_{2.5}$ and PM_{10} concentrations and noise levels at the three toll booths. Further, mathematical formulations were used for the assessment of fuel wastage at the selected toll booths. For assessment of fuel wastage and cost incurred due to waiting at toll plazas on Indian national highways, various observations were taken at each of the selected toll booths. The average waiting time in a queue for a vehicle and length of the queue were observed at all the three selected toll booths for different time clusters per day as of the survey of the peak and off-peak hours. The data for the total number of vehicles passing per day from a toll booth was retrieved from the website of Toll Information System-National Highways Authority of India (Toll Information system, 2017*)*. Various assumptions were made over the observed data, so the results assessed are subject to the assumptions made.

Mathematical formulations for fuel wastage due to toll booths

The present era is experiencing a fast degradation of non-renewable resources in terms of fossil fuel. As the primary energy source, the continuous use of fossil-based fuels not only led the world to a severe condition of fuel crisis but also offers another primary concern of environmental degradation. The continued exhaustion of fossil-based fuel also resulted in a subsequent upsurge of exhaust gasses and emerged as a major factor for global warming (Gonçalves and Simões, 2017). Researchers are putting effort all over the globe to save any potential wastage of fossil-based fuels. This study presents an assessment of fuel wastage due to vehicle idling at road toll that can aid in finding solutions for restricting the fuel wastage. In the present study for analysis of fuel wastage, various assumptions were made as; 1) All the vehicles were considered to be of similar types of passenger vehicles. 2) The fuel efficiency of the vehicles (f^e) was assumed as constant 16 km/L. 3) The average vehicular cruising speed in non-idling conditions (v^s) was assumed as 60 km/h) The vehicle engine assumed to be remained on during idling conditions throughout the waiting time. Several observations were made at all the three selected toll booths, and their mean values were considered for calculating the average waiting time for a vehicle in a queue at toll (q^μ), and length of the queue in meter (q^L), in each of the selected toll booths. With observations over all the three tolls, the average waiting time, q^μ and queue length of vehicles q^L, in ETC (Electronic Toll Collection), and manual lanes came approximately the same. The approximate total number of vehicles passing per day at the tolls (T^v) was retrieved from the website of Toll

Information System-National Highways Authority of India (Toll Information system, 2017). For estimations of fuel consumption with vehicle idling at tolls and savings of fuel when no tolls were present, average fuel consumed per hour by passenger vehicle in an idling condition (c^t) was calculated which was used to determine the fuel consumption of each of the vehicle while idling in the queues at toll (c^q), and fuel consumption of each vehicle if there was no toll (c^n). If no tolls are present, average fuel saved per vehicle (s^v), total fuel saved per day (s^d), and total fuel saving per year (s^y), were assessed. It was assumed that fuel efficiency (f^e) was16 km per liter, and average vehicular cruising speed (v^s) was 60 km per hour, so average fuel consumption for a vehicle per hour, considering vehicle was running at assumed speed throughout the hour became 3.75 liters per hour. According to Tong *et al.* (2000), in their defined conditions, for a passenger vehicle, the fuel consumption rate while cruising the vehicle is 39.10 gram per km, and at idling, the condition is 18.11 gram per km. It can be deduced from the results of Tong *et al.* (2000) that idling condition fuel consumption is 46.32 percent of the fuel consumption in the cruising conditions. If not considering the fuel consumption rates at accelerating and decelerating conditions of vehicles, the average fuel consumption for a passenger vehicle at idling condition (c^t) will be 46.32 % of the cruising speed condition making c^t equals to 1.737 liters per hour. With the provided assumptions, fuel consumed per vehicle while the vehicle is in the queue at the toll (c^q) was calculated in liter as the product of the average waiting time of the vehicle and average fuel consumption for a vehicle per hour in idling condition using Eq. 1.

$$c^q = q^\mu * c^t \quad (1)$$

Total fuel consumed per vehicle in liter if no tolls were present (c^n) was calculated as the ratio of the length of the road where the queue was there to fuel efficiency of the vehicle using Eq. 2.

$$c^n = q^L / f^e \quad (2)$$

Through, Eqs. 1 and 2, the total fuel saved per vehicle (s^v) in liter was calculated as the difference of the fuel consumed while a vehicle has to go in the queue if the toll was present to the fuel consumed by the vehicle if no toll was present, using Eq. 3.

$$s^v = c^q - c^n \quad (3)$$

Through Eq. 3, total fuel that can be saved in liter at each of the tolls was calculated as the product of total fuel saved per vehicle and the total number of vehicles passing through each of the tolls per day, using Eq. 4. The outcome was multiplied with 365 to get the total fuel that can be saved over the toll booths in a year, using Eqs. 5.

$$s^d = s^v * T^v \quad (4)$$

$$s^y = s^d * 365 \quad (5)$$

Using the equations (4) and (5), total fuel costs that can be saved per day and per year, if no toll was present, can be calculated by multiplying s^d and s^y with the fuel price per liter, respectively.

Measurement of noise levels and $PM_{2.5}$ and PM_{10} levels at toll booths

For measurement of noise levels at the selected toll booths, a sound level meter Extech SL10 was used, which is a pocket-sized handheld device for computing the sound levels. Extech SL10 sound meter has a measurement bandwidth of 31.5Hz to 8 KHz with a range of 40dB to 130dB operated over an A-weighting frequency. Frequency weightings for different noise meters are associated with the human ear response boundaries, and A-weighting frequency is the most common frequency used in most of the noise or sound meters (Pierre Jr and Maguire, 2004). Extech SL10 is accurate to ±3.5dB under reference conditions of 94dB and functions at operating temperature in between of 0 to 40° Celsius and operating humidity of 10 to 90 percent RH. For analysis of sound levels at all the three toll plazas – Lalanagar, Dafi, and Mohania, the calibrated SL10 was used to record the sound levels in the Max-Min mode, which measures the maximum and minimum sound levels over the area. From the survey results of peak hours and off-peak hours of the selected road toll plazas, five-sound samples of maximum levels were collected in each of the peak and off-peak time for 20 days during the period of 10 May 2017 to 14 July 2017. The samples were collected in intervals of 10 minutes, and the timing in seconds was recorded

for different sound levels in decibels(dB) at the toll plazas. Mean of the 20 days' sample for a daily average of the 10 sample data collected in the peak and off-peak time were used for analyzing the level of noise pollution over the three toll plazas. For measurement of $PM_{2.5}$ and PM_{10} at the road tolls, HT-9600 particulate matter particle counter was used. Benefits associated with a particle counter are that it is easy to operate, moveable, and easy to carry, less costly and efficient in measuring concentrations of the particles for short time intervals (Tittarelli *et al.*, 2008). HT-9600 counts in 3 channels with a particle size of 0.3, 2.5, and 10 µm. HT-9600 particle counter comes with an optoelectronic type sensor with a laser diode as a light source. It measures the particle in microgram per meter cube (µg/m^3) and has a measurement range of 0 to 10000 µg/m^3. The instruments' flow rate of air samples is 1 liter/min and has a pre-defined sampling time of 50 seconds. So for HT-9600, all the readings were multiplied by a ratio of 6/5 and were rounded off for getting the 1-minute concentration of $PM_{2.5}$ and PM_{10}. With the instruments HT-9600, ten samples were taken for the three selected toll booths in a day distributed as five samples over the peak and off-peak times for 20 days from the period of 10 May 2017 to 14 July 2017. Mean values of per day 10 sample readings had given the 1-minute average concentrations of PM_{10} and $PM_{2.5}$ particles in µg/m^3 units. This mean 1-minute values of $PM_{2.5}$ and PM_{10} were used as day-average particulate matter particles for the analysis of the results.

RESULT AND DISCUSSION

Results of the study

In this section of the study, results are estimated and analyzed for the total fuel wastage due to the vehicle delays at toll booths of Lalanagar Toll Plaza, Dafi Toll Plaza, and Mohania Toll Plaza, on Indian National Highways 19 (NH-19) near to district Varanasi. Noise levels and concentration levels of $PM_{2.5}$ and PM_{10} are also assessed for the selected three toll booths in this section. Table 1 presents the results of the initial survey to identify peak hours of vehicle movement at three toll booths. The survey was conducted with the toll booth operators and workers of the three toll booths. As per Table 1, it can be observed that all the three toll booths are having a good number of peak hours with 6-8 hours of excessive traffics at these toll booths daily. Many times during peak hours, these toll booths observe long waiting queues of vehicles. Even in off-peak hours, it was found good and continuous traffic over these tolls leading to significant fuel wastage, air and noise pollution.

Fuel wastage at the toll booths

Taking several observations at each of the three toll booths in their respective peak hours and off-peak hours, average waiting time (q^{μ}) and length of the queue (q^{L}) were calculated and are presented in Table 2. The total number of vehicles passing per day at the toll booths (T^{v}) is as well presented in Table 2. As per the available data on the official website of *Toll Information System* of *Government of India*, Dafi toll plaza observed passing of 45468 vehicles, last recorded on 20th March 2017, Lalanagar toll plaza observed passing of 33287 vehicles, last recorded on 26th of May 2017, and Mohania toll plaza observed passing of 39705 vehicles last recorded on 21st April 2017 (Toll Information system, 2017). It can be observed from the results presented in Table 2 that Dafi toll plaza has the highest waiting time for a vehicle and apparently the most extended average length of the queue among all the three toll plazas. Mohania toll plaza has the second-highest waiting time, and average queue length followed lastly by Lalanagar toll plaza. A perceived reason behind high waiting time at Dafi toll plaza is that this particular toll is closest to the district Varanasi and traffic of the city very much impact the toll in comparison to the other two. Further, the results presented in Table 2 shows

Table 1: Vehicle peak hours at the three toll booths

Toll Booth	Peak Hours	Total Peak Hours
Lalanagar Toll Plazas	08:00-11:00, 16:00-20:00	7 Hours
Mohania Toll Plaza	09:00–11:00, 17:00-19:00 and 22:00–00:00;	6 Hours
Dafi Toll Plaza	08:00-11:00, 17:00-19:00 and 22:00-01:00	8 Hours

Table 2: Fuel consumption and amount of fuel wastage at the three toll booths

Particulars	Dafi Toll Plaza	Lalanagar Toll Plaza	Mohania Toll Plaza
Total number of vehicles passing per day at the toll booths (T^v) (Toll Information system, 2017)	45468 vehicles	33287 vehicles	39705 vehicles
Average waiting time for a vehicle in a queue at the toll booth (q^μ)	618 seconds	155 seconds	232 seconds
Average length of the queue (q^L)	295 meter	84 meter	127 meter
Fuel consumption per vehicle while vehicle be in queue at the toll booth (c^q)	0.299 liter	0.075 liter	0.11 liter
Total fuel consumption per vehicle if no toll booths were present (c^n)	0.079 liter	0.022 liter	0.034 liter
Total fuel that can be saved per vehicle in the absence of toll booths (s^v)	0.22 liter	0.052 liter	0.077 liter
Total fuel that can be saved per day (s^d)	10002.96 liter	1730.924 liter	3057.285 liter
Total fuel that can be saved per year (s^y)	3651080.4 liter	631787.26 liter	1115909.025 liter

that in a single day, these three toll plazas account for a total fuel wastage of 14791.17 liters of fuel in which the Dafi toll contributes maximum wastage of 10002.96 liters. Lalanagar toll contributes wastage of 1730.924 liters, and the Mohania toll contributes wastage of 3057.285 liters. The collective fuel that can be saved in the absence of these three toll booths in a year is approximately 5398776 liters of fuel. The statistics presented in Table 2 shows the gravity of the fuel wastage problem due to toll booths on highways.

PM particles pollution at the toll booths

Leading to more adverse effects of toll booths other than fuel wastage, Fig. 2 shows the amount of particulate matter particles ($PM_{2.5}$ and PM_{10}) observed at each of the three selected toll booths near Varanasi. From the line graph of Fig. 2, it is evident that $PM_{2.5}$ and PM_{10} levels are comparatively higher at Dafi toll plaza, followed by Lalanagar Toll Plaza and Mohania Toll Plaza. Fig. 2 also shows a very high concentration level of both the $PM_{2.5}$ and PM_{10} particles at all the three toll plaza. The variations of $PM_{2.5}$ were mostly observed between 150 µg/m^3 to 350 µg/m^3, with few observations also detected exceeding 350 µg/m^3. The observed variations of PM_{10} ranged in between 200 µg/m^3 to 400 µg/m^3, with several observed concentrations exceeding the levels of 400 µg/m^3. According to the report of Cardinal (2018), mapping the pollution concentrations with AQI values is presented in Table 3. The air quality index with respect to different pollutants is categorized into six categories of 'good,' 'moderate,' 'unhealthy for few,' 'unhealthy,' 'very unhealthy' and 'hazardous.' Below 35.5 µg/m^3 for $PM_{2.5}$ and below 155 µg/m^3 for PM_{10} is considered better standard for both the PM particles. On comparing the observed particulate matter particle levels with the standard values presented in Table 3, it is very much clear that the observed levels of $PM_{2.5}$ and PM_{10} at all the three tolls lied in 'very unhealthy' to 'hazardous' categories. The results show that not a single observation found at all the three tolls lied in the categories of 'good' or even 'moderate,' proving the extremely polluted conditions in terms of PM particles over these toll booths. The aggregate mean of all the observed concentration levels of $PM_{2.5}$ and PM_{10} also shows severe conditions compared to the standard levels in AQI mapping. The aggregate mean of all the observed levels at the Dafi toll booth for $PM_{2.5}$ is 279 µg/m^3 and for PM_{10} is 384.35 µg/m^3; at Lalanagar toll booth for $PM_{2.5}$ is 232.7 µg/m^3 and for PM_{10} is 329.7 µg/m^3 and at the Mohania toll booth for $PM_{2.5}$ is 194.8 µg/m^3 and for PM_{10} is 287.8 µg/m^3. The aggregate mean PM_{10} level of all the mean observed concentrations lied in the 'very unhealthy' category, whereas for $PM_{2.5}$, the Dafi toll booth lied in the 'hazardous' category, Lalanagar toll booth lied in the 'very unhealthy' category, and Mohania toll booth lied in 'unhealthy' category.

Noise levels at the toll booths

The standard value of ambient noise varies with respect to different regions and demographic zones.

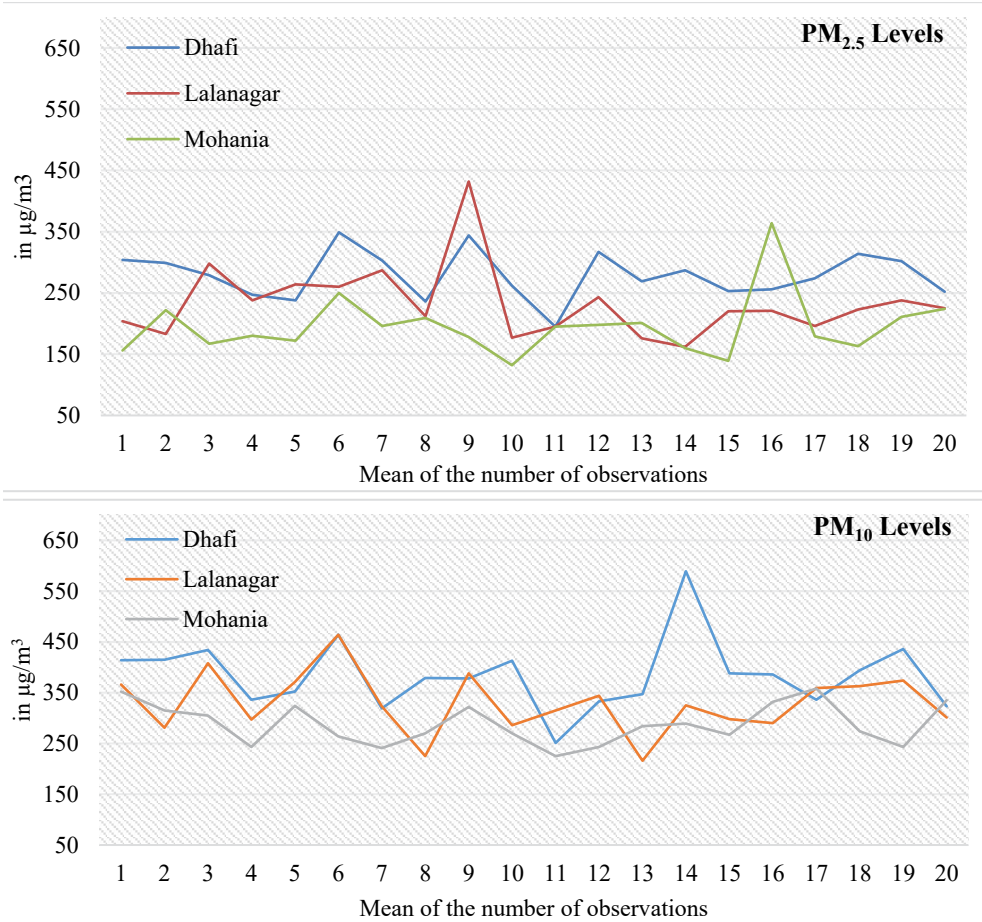

Fig. 2: $PM_{2.5}$ and PM_{10} levels in µg/m³ for the experimental study using HT-9600

Table 3: $PM_{2.5}$ and PM_{10} in µg/m³ mapping with AQI categories (Cardinal, 2018)

$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	Category
$C_{low} - C_{high}$	$C_{low} - C_{high}$	
24 h average	24 h average	
0.0 -12.0	0-54	Good
12.1-35.4	55-154	Moderate
35.5-55.4	155-254	Unhealthy for sensitive groups
55.5-150.4	255-354	Unhealthy
150.5-250.4	355-424	Very unhealthy
250 above	425 above	Hazardous

For average noise exposure, WHO, (2018) report acclaims that the noise generated by road traffic should be below 53 dB. The report mentioned that continuous exposure to high decibel sound levels of road traffic could lead to adverse health effects. According to National Institute on Deafness and Other Communication Disorders, in general terms below 85 dB noise can be considered as safe sound levels, and prolonged exposer to sound levels of 85 dB or above can cause severe hearing issues (Fink, 2017). In India, ambient noise is categorized under four areas that are industrial, commercial, resident,

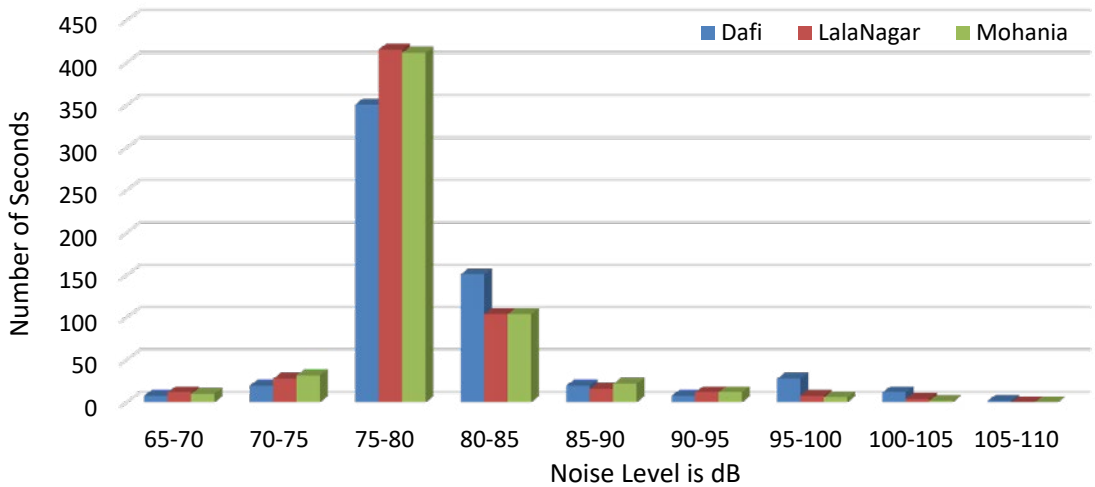

Fig. 3: Number of seconds of noise levels in dB in 10 min interval using Extech SL10

and silence zone. Toll booths can be considered under commercial area, and for it, the standard values of noise are 65 dB in the day and 55 dB in the night (Noise Pollution Rules, 2000). Noise levels at the three respective toll booths were observed significantly higher than the standard noise levels that can lead to severe problems to the toll workers. Fig. 3 shows the bar graph of sound levels in decibels (dB) of the three selected toll plazas. The noise levels in between 75 to 80 decibels have the highest percentage in the 10 minutes (600 seconds) mean readings for all the three toll plazas with 351 seconds at Dafi toll, 416 seconds at Lalanagar toll and 412 seconds at Mohania toll. The second-highest percentage of mean observed readings is between 80 dB and 85 dB. Mean reading values have shown a noteworthy percentage of noise levels above 85 decibels up to a maximum of 110 decibels with 70 seconds at Dafi, 40 seconds at Lalanagar, and 42 seconds at Mohania tolls. The results presented in Fig. 3 shows all mean reading above the 53 dB levels. With respect to the noise pollution standards by Noise Pollution Rules, (2000), the results from the study show that only 1.33 percent duration of noise levels at Dafi toll, 2 percent duration of noise levels at Lalanagar toll, and 1.66 percent duration of noise levels at Mohania toll were under the standard levels of noise. The noise levels obtained in the study proved to be unsafe and can cause several health issues to public health as well as can cause severe hearing aids to toll booth workers.

Discussion on the results of the experimental study

The results of the study confirmed various other past studies that have observed critical conditions of air pollution, specifically PM particles at toll booths (Lin et al., 2020; Wang et al., 2020). The hazardous levels of both $PM_{2,5}$ and PM_{10} at all the three toll booths observed in the study show the possibility of health issues like pulmonary health problems, as stated by Belloc-Santaliestra *et al.* (2015) to toll tellers and highway workers. The results presented in the above section of the study suggest the requirement of strict actions for controlling the pollution and wastage of fuels at toll booths. Fuel wastage at an intersection point or toll booths can be little for a vehicle, but collectively for hundreds of vehicles, it turns up to be a great source of potential fuel wastage (Sharma *et al.*, 2018). Results presented in Table 2 of the study confirms by showing the magnitude of fuel wastage in a day and a year over the selected three road tolls. The observed fuel wastage at all the three toll booths suggests necessary and specific measures. Works of Blanc (1987); Chakroborty *et al.* (2016); Conolly (1984); Edie (1954); Fu and Gu (2017); Haight (1958); Jaiswal *et al.* (2019a); Jaiswal *et al.* (2019b); Schwartz (1974) and others can be assessed for finding possible solutions for minimizing traffic congestions leading to lesser fuel wastage at toll plazas. With the absence of the road tolls or by making a strategy such a way that no vehicle has

to stop over the road tolls, an enormous amount of these non-renewable fuels can be saved along with meaningfully contributing to the supply chain economy. The Government of India has taken a very serious step by the mandatory implementation of FASTag: an electronic toll collection at road toll medium from December 15, 2019 (Oza, 2020). Still, long queues of vehicles can be observed over road toll booths leading to vehicle idling and ultimately leading to wastage of fuel and vehicular pollution generation. As per as vehicular pollution is concern, while the Government of India already puts serious efforts to minimize vehicular pollution by promoting the use of E-vehicles and alternate transportation medium (Shalender and Yadav, 2018), discontinuing the use of the poor environmental standard of vehicles (Jaiswal *et al.*, 2019a), mandatory adoption of FASTag system on road tolls (Algonda *et al.*, 2018) and various other measures. Still, more efforts are required to curb vehicular pollution, and reducing vehicular pollution generation at a toll can be very significant in this order. Results from the study of Jaiswal *et al.* (2018) has shown that the air pollution, especially particulate matter particles ($PM_{2.5}$ and PM_{10}) are a severe concern at present as well as in the future for the district Varanasi, and the study presented in this work proved tolls nearby Varanasi is a significant contributor of $PM_{2.5}$ and PM_{10}. The study shows that any work reducing PM emissions at tolls of Dafi, Lalanagar and Mohania can considerably contribute to the reduction of overall PM levels at Varanasi. On a comparison among the selected three tolls, the Dafi toll booth has the worst conditions in terms of PM particle levels. Since it is the closest to the city Varanasi, the toll also very much adds PM particles in the city's urban environment. Considering the research study of Jaiswal *et al.* (2018), all efforts in reducing the air pollution at the Dafi toll will considerably contribute to improving the urban ambient environment of Varanasi. Besides, the toll booth workers are the first and potential victim of both the vehicular air pollution and noise pollution due to the continuous and vast number of vehicles passing and idling at the toll booth. The issue of sound pollution over toll booths has been addressed by various past research works (Kim *et al.*, 2016; Meier *et al.*, 2013) for different countries, and the presented study adds to the existing problem and proves that a serious solution to the issue is required. The noise levels detected at all the three toll booths are in accordance with the concerns raised by Fider *et al.* (2017) and Feist *et al.* (2001). The observed results show that the noise levels at all the three toll booths are much higher than the standard sound levels of 65 dB at day and 55 dB at night, as recommended by The Noise Pollution [Regulation and Control] Rules, (2000), Government of India. As India is concerned, past studies have proved the seriousness of high noise levels at traffic in India (Agarwal *et al.*, 2017; Kumar *et al.*, 2017; Tandel and Macwan, 2017). This work presented in this study adds to the literature about the concerns of higher noise levels, particularly at the road toll booths.

The implications of the study show that specific remedial measures are required at Dafi, Lalanagar, and Mohania toll booths for air pollution, noise pollution, and fuel wastage control. The study infers that with the control of PM particle emissions at the three toll booths, a significant improvement in the AQI of Varanasi can be observed. The study also infers that with the reduction of vehicle idling at road toll booths in India, a substantial amount of fuel can be saved from wastage along with controlling the air and noise pollution of urban areas. The following are the few remedial measures that can be considered for mitigating air and noise pollution along with controlling fuel wastage due to vehicle idling at road tolls.

- Restricting the manual operations of toll collections and mandatory implementations of FASTag electronic toll collections (Algonda et al., 2018) for all vehicles over every toll booth.
- Development of dedicated lanes for heavy traffic. Many of the countries are already using the dedicated lanes approach and the results are commendable in terms of pollution and fuel wastage reduction (Figueiras et al., 2019).
- Removal of toll booths and toll collection on the basis of distance traveled (Andrlík and Zborovská, 2019).
- Dynamic toll pricing for and congestion pricing in which road toll taxes are changed according to traffic congestion conditions to reduce vehicle idling at tolls leading to a decrease in pollution and fuel wastage (Chang and Hsueh, 2006; Zhang and van Wee, 2012).
- Restricting the use of lower environmental

standard vehicles (Jaiswal *et al*., 2019a) and encouragement towards the use of E-vehicles and alternate transportation medium (Shalender and Yadav, 2018).

- Including the strategies of polluter pay over road tolls to check and encourage commuters to control air and sound pollution (Andrlík and Zborovská, 2019).
- Use of engineering control method for confining toll plaza windows to obstruct noise transmission to reduce the effects of vehicle noise pollution (Fider *et al*., 2017) and use of active noise control headset (Feist et al., 2001).

CONCLUSION

Fuel wastage, PM particle pollution, and noise pollution were assessed over three toll booths on NH-19 around the district Varanasi in India in this study. The three selected toll booths of Dafi toll, Lalanagar toll, and Mohania toll over the national highway of India were assessed using device Extech SL10 for measuring noise levels, HT-9600 Air Particle Counter for evaluating $PM_{2.5}$ and PM_{10} levels and queuing model approach for calculating fuel wastage. The results presented in the study shows significant pollution levels for both PM particles and noise levels. The study also shows a good amount of vehicular fuel wastage at all three toll booths. For PM_{10} and $PM_{2.5}$, the analyzed data revealed very severe levels for the pollutants with all the average readings in the category of unhealthy to very unhealthy and even in hazardous conditions. These high levels of air pollution over toll booths not only cause health effects to the workers but also significantly contribute to deteriorating the ambient environment surroundings. Besides PM particle pollution, the presented study also shows the severity of noise pollution over the toll booths. The prolonged stay in such detrimental surroundings will have a direct effect on the health of toll booth workers. Other than pollution, the study emphasized on fuel wastage due to vehicle idling over the toll booths. The results presented in the study assessed enormous wastage of fuel over each of the three toll booths. The formulations for assessment of fuel wastage are limited to the assumptions made but still proved the necessity of real-time solutions for vehicle idling at tolls that will not only avoid fuel wastage but will also significantly contribute to reducing the time of transportation contributing in improving the logistical activities. The study presented in the paper is limited to a small number of data collected. The study is also limited to the assumptions made in the formulation model of fuel wastage due to vehicle idling at toll booths. Also, the study is carried out before the mandatory implementation of FASTag on road toll booths in India. In the future work of the study, a new data set can be collected with FASTag electronic toll collection medium over toll booths and can be compared with the results of this study.

AUTHOR CONTRIBUTIONS

A. Jaiswal performed the manuscript writing, collected the data and done the partial analysis work of the study. C. Samuel carried out the analysis presented in the study and also edited and corrected the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

%	Percent
°	Degree
&	And
$\mu g/m^3$	microgram per meter cube
μm	micrometer
AI	Artificial Intelligence
AQI	Air Quality Index
C_{low}	Concentration low
C_{high}	Concentration high
c^n	Fuel consumption of each vehicle if there was no toll

c^q	Fuel consumption of each of the vehicle while idling in the queues at toll
c^t	Average fuel consumed per hour by passenger vehicle in an idling condition
dB	Decibel
DNA	Deoxyribonucleic acid
ETC	Electronic toll collection
Eq	Equation
Eqs	Equations
E-vehicles	Electronic vehicles
f^e	Fuel efficiency of the vehicles
h	hour
Hz	Hertz
IIM	Indian Institute of Management
KHz	Kilo hertz
km	Kilometer
km/L	Kilometer per liter
kmph	Kilometer per hour
min	minute
NH	National Highway
NOx	Nitrogen Oxides
PM_{10}	Particulate matter particle up to size 10 micrometer
$PM_{2.5}$	Particulate matter particle up to size 2.5 micrometer
q^L	Length of the queue in meter
q^u	Average waiting time for a vehicle in a queue at toll
RH	Relative humidity
s^d	Total fuel saved per day
s^v	Average fuel saved per vehicle
s^y	Total fuel saving per year
T^v	Total number of vehicles passing per day at the tolls
v^s	Average vehicular cruising speed in non-idling conditions
USD	United States Dollar

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ORIGINAL RESEARCH PAPER

Two-dimensional flood model for risk exposure analysis of land use/land cover in a watershed

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ABSTRACT

BACKGROUND AND OBJECTIVES: The study involved developing a two-dimensional flood model to analyze the risk exposure of land use/land cover based on the generated flood hazard maps for the six return period scenarios in the Solana watershed.

METHODS: The approach consisted of applying hydrologic and hydraulic numerical flood models and the suite of advanced geographic information systems and remote sensing technologies. The process involved utilizing a high-resolution digital elevation model and a set of high-precision instruments such as the real-time kinematic-global position system receiver, digital flow meter, deep gauge, and automatic weather station in collecting the respective data on bathymetry, river discharge, river depth, and rainfall intensity during a particular climatic event, needed for the model development, calibration and validation.

FINDINGS: The developed two-dimensional flood model could simulate flood hazard with an 86% accuracy level based on the coefficient of determination statistics. The flood risk exposure analysis revealed that coconut is the most affected, with 31.3% and 37.1% being at risk across the 2-year and 100-year return period scenarios, respectively. Results also showed that rice and pineapple are at risk of flooding damage with the increasing rate of exposure by a magnitude of 42.9 and 9.3 across the 2-year and 100-year flood scenarios, respectively.

CONCLUSION: The study highlighted the integration of the findings and recommendations in the localized comprehensive land use plan and implementation to realize the challenge of building a climate change proof and a flood-resilient human settlement in the urbanizing watershed of Solana.

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INTRODUCTION

Catastrophic floods following torrential rains brought by climate change-induced typhoons have recently recurred in the regions of Southeast Asian countries. The Philippines is one of the Southeast Asian countries recently hit by floods due to the three successive typhoons, namely Quinta, Rolly, and Ulysses, internationally known as Molave, Goni, and Vamco, respectively (De Vera-Ruiz, 2020; Teves, 2020). Disastrous floods brought about by these typhoons made the situation of the country worse amid coronavirus disease 2019 (COVID-19) pandemic. About millions of Filipinos moved to the evacuation facilities for safety, but their properties remained exposed to flood hazards and are at risk of devastation. Monitoring and assessing the affected areas for relief goods distribution and other possible mitigation purposes are the immediate disaster responses by the government and non-government organizations. In aid of legislation, academic institutions and research units may have to conduct a more detailed risk exposure analysis and assessment of the inundated sites using a standard set of statistical and flood modeling tools like the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and HEC-River Analysis System (Gumindoga *et al*., 2017; Khalfallah and Saidi, 2018). However, flood modeling for risk exposure analysis requires specific expertise and experience (The World Bank, 2016). The research team must have the basics in modeling, with background on the different climatic and hydrologic parameters, including the processes and the application of hydrologic and hydraulic models, geographic information systems (GIS), and remote sensing tools. The types of computer application software, equipment, and input data are also important factors that could affect the accuracy and validity of the final flood model (Ogania *et al*., 2019). Even with the availability of the above procedure, several flood modeling and simulation studies failed to elaborate the use of high precision real-time kinematic-global positioning system (RTK-GPS) equipment and high-resolution digital elevation model (DEM) data such as those derived from airborne light detection and ranging (LiDAR). The reason for this is the unavailability of high-resolution DEM data in some areas. For example, some flood modeling studies used low-resolution DEM such as those derived from Shuttle Radar Topography Mission and Synthetic Aperture Radar technologies (Zhang *et al*., 2019; Laks *et al*., 2017; Musa *at al*., 2015). The type of data, modeling protocols, and equipment used will eventually affect the reliability of results and the acceptability of the entire process of a GIS-based technique of flood risk exposure analysis and assessment. As reviewed, flood risk analysis and assessment is an emerging scientific discipline that emphasizes GIS, with some limitations, as the most promising tool having the capability to integrate all the other techniques (Diez-Herrero and Garrote, 2020). Appropriate flood modeling and hazard map generation techniques could enhance the risk exposure analysis and assessment study results, specifically with the use of high-resolution DEM and application of high precision surveying equipment, hydrologic and hydraulic models, and the combined technologies of GIS and remote sensing (Puno *et al*., 2019; Puno *et al*., 2018; Santillan *et al*., 2016). Nevertheless, regardless of methods limitations such as the unavailability of high-resolution LiDAR data and high-precision survey instrument like RTK, flood modeling, as an initial step, is essential to generate a hazard map for flood risk exposure and analysis of the inundated land use/land cover (LULC) within the watershed. Land use includes built-up areas, roads, bridges, buildings, and other infrastructures, while land cover comprises different types of vegetation like the forest, grasslands, agro-industrial, and other crop plantations (Israel and Briones, 2013). In the past few years, risk exposure and assessment projects in the Philippines enabled the generation of highly detailed flood hazard maps through LiDAR data (Sarmiento *et al*., 2015). The method allows the collection of high-resolution DEM data appropriate as input in the flood modeling simulation and hazard map generation using the hydrologic model and GIS technique. These programs/projects include the University of the Philippines Disaster Risk and Exposure Assessment for Mitigation (UP-DREAM) and its expansion, the Philippine Light Detection and Ranging 1, and the Geo-Informatics for the Systematic Assessment of Flood Effects and Risks for a Resilient Mindanao (Geo-SAFER Mindanao). On top of producing highly detailed flood hazard maps and updated high-resolution DEM covering two-thirds of the country's critical river basins and other priority areas, the above projects aimed at analyzing flood risk exposure of the affected LULC within the basins. The government and some non-government organizations have collaborated to conduct research programs deliberately to evaluate

the condition of LULC in the aftermath of flood hazards. The extent of damages to the affected LULC usually serves to account for the impact of the disaster on the local and national economies (Svetlana *et al*., 2015). Researchers worldwide have conducted flood risk exposure analysis and assessment studies to evaluate the vulnerability of LULC to flood hazards (Mousavi *et al*., 2019; Pant *et al*., 2016). As suggested from the previous study, the multi-criteria approach could improve the methods especially those involving decision-making relative to proper land-use zoning for flood mitigation (Motlagh and Sayadi, 2015). However, this study focuses only on developing a flood model as a basis for the risk exposure analysis of LULC in the Solana watershed. This paper presents the methods of developing, calibrating, and validating a two-dimensional (2D) flood model to analyze the risk exposure of LULC based on the hazard maps for the six return period scenarios. The procedures involved using hydrologic and hydraulic models such as HEC-HMS and HEC-RAS, respectively, within the GIS environment. The study covered the two municipalities of Claveria and Jasaan, Misamis Oriental, for one year in 2018-2019. This study expects the utilization of information on flood risk exposure analysis by the policy- and decision-making authorities in the quest of building an ecologically sustainable and flood-resilient community.

MATERIALS AND METHOD

The study watershed

The study team selected the Solana watershed as the study site due to the periodic occurrence of fluvial flooding, causing inundation in the floodplain. Furthermore, the Environmental Management Bureau-Department of Environment and Natural Resources (EMB-DENR) prioritizes the river of Solana watershed to be under the water quality monitoring program of the government through its memorandum dated June 8, 2016. The area belongs to a tropical rainforest climate with an average daily temperature of 25°C. The rainfall is evenly distributed throughout the year with monthly average accumulations of 18.29 mm. The topography of the upper watershed is characterized by gently rolling hills and mountain ranges. The soil, particularly in Claveria is classified under Jasaan Clay with a deep of Ultic Haplorthox (Delgado and Canters, 2012). The Solana river under normal flow has an average of approximately 1.0 m^3/s and peaks at 4.32 m^3/s during an event. The watershed location is at the north-central of Misamis Oriental Province (Fig. 1). It lies between 124° 45' 46.02" to 124° 54' 45.33" east longitude and 8° 39' to 8° 35' north latitude, having a length of 17.60 km and a width of 3 km, and an estimated drainage area of 67.65 square kilometers. The watershed traverses the municipalities of Claveria and Jasaan of Misamis Oriental and drains into the Macajalar Bay.

Data for flood modeling

The process of flood risk exposure analysis consists of primary and secondary data collection and preparation. The collected sets of secondary data included the high-resolution DEM, soils, Sentinel 2 satellite image of land cover from the United States Geological Survey Earth Explorer, and the historical rainfall intensity duration frequency (RIDF). These

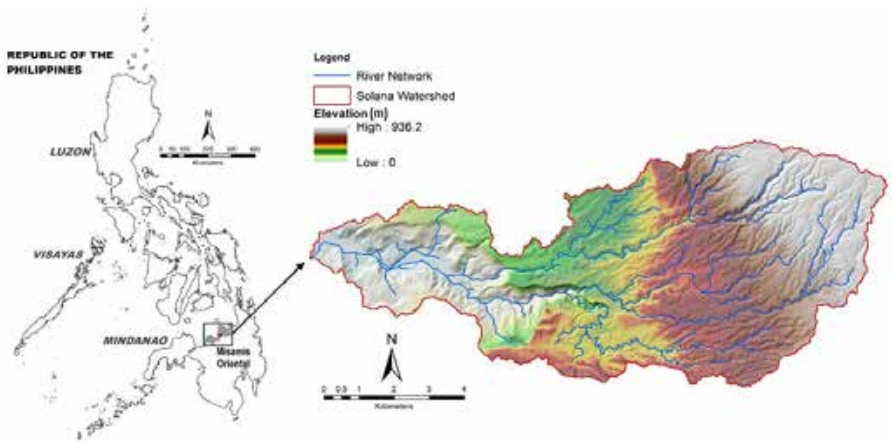


Fig. 1: Geographic location of Solana Watershed in north-central Misamis Oriental, Philippines

data were processed and prepared according to the set of procedures required in the modeling activity. The additional primary datasets included the rainfall intensity, river depth, and velocity during a particular event, bathymetric data, and the measurements of the river's cross-section and profile.

DEM and soils map acquisition

The DEM map layer consists of two categories, the 5-meter resolution interferometric synthetic aperture radar (IFSAR) and the 1-meter resolution derived from LiDAR technology. The National Mapping and Resource Information Authority (NAMRIA) had provided the IFSAR data for the hydrologic modeling of the watershed. In contrast, the UP DREAM program had made the LiDAR data available for the hydraulic modeling component. The Bureau of Soils and Water Management had provided the soil map with the corresponding database.

LULC map generation and validation

The study used the July 26, 2017, sentinel-2 satellite image product from the United States Geological Survey (USGS) Earth Explorer to generate the LULC map for the whole modeled watershed. The team chose the image because it was available being free from cloudiness and other obstruction. The Sentinel-2A is an advanced satellite image with a resolution applicable for various remote sensing applications (Nguyen *et al*., 2020; Puno, *et al*., 2019; Addabbo *et al.,* 2016). This step included pre-processing of satellite images to correct single-date sentinel-2A level-1C products from the effects of the top of atmosphere (TOA) reflectance. The product output was the sentinel-2A level-2A with the bottom of atmosphere (BOA) reflectance. TOA to BOA involved the use of a processor (Sen2Cor) running on the European Space Agency's (ESA) sentinel-2 toolbox using the sentinel application platform (SNAP) software (Warren *et al*., 2019). The level-2A output product includes the bands with three different resolutions (60m, 20m, and 10m). The 10-meter resolution bands, namely red, green, and blue (RGB) and near-infrared (NIR), were layer-stacked and exported in tag image file format (TIFF) as the final image utilized during the LULC classification. Also, the Green-red vegetation index (GRVI) and normalized difference vegetation index (NDVI) were derived from the sentinel-2 imagery to enhance further the LULC classification accuracy (Sothe *et al*., 2017; Zhang *et al*., 2017). This step performed an object-based image analysis using eCognition Developer version 9.0.1 to produce an output consisting of the grouping pixels as a segment rather than individual grids with combined spectral, spatial, and contextual information (Phiri and Morgenroth, 2017). The applied classification algorithm was the support vector machine (SVM), which provides better classification results and outperformed other classifiers such as the pixel-based maximum likelihood classifier (Ji *et al*., 2019; Bahari *et al*., 2014; Shi and Yang, 2015). SVM involves training sample collection from pixels of the image used to establish threshold as the basis of delineating specific land cover classes. The next phase consisted of collecting validation sample points of different land cover classes on the ground, independent from training samples collected based on the image of google earth aerial photos. The process involved applying the confusion matrix analysis using the training and validation sample points to obtain the producer, user, and the overall accuracy values (Janiola and Puno, 2018). The producer accuracy refers to the probability that a particular land cover class of an area on the ground is classified as such, while the user accuracy refers to the likelihood of the same identity between a pixel and the actual land cover class in the map (Rwanga and Ndambuki, 2017; Bogoliubova and Tymkow, 2014). The LULC classification output using eCognition produces several segmented objects as polygons where some are irrelevant in the map layout. Thus, the process applied the minimum mapping unit tool within the ArcGIS 10.2 to decongest the map from irrelevant segmented polygons. The process is necessary for the overall LULC classification to visually and spatially reduce the complexity of the information contained in the final map (Garcia-Alvarez *et al*., 2019).

Event and bathymetric data collection

The modeling team also collected data from a particular event like rainfall intensity, river depth, and velocity from the installed automatic weather station, digital depth gauge, and digital velocity meter, respectively. The study also obtained the RIDF from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAG-ASA). The team conducted the actual field survey of the channel cross-section and river reach using a high precision

RTK-GPS receiver instrument to collect bathymetric and river profile data.

Flood model development, calibration, and validation

The flood modeling component of this study involved two processes, that is, hydrologic and hydraulic model development. The modeling protocols applied the two open-source sets of computer utilities. The first set consists of the HEC-HMS responsible to simulate river discharge (Gumindoga *et al*., 2017). The second set comprises the HEC-River Analysis System version 5.0 (HEC-RAS 5.0) responsible to simulate a 2D flood model domain (Khalfallah and Saidi, 2018). Both models have the geospatial interface as an extension of ArcGIS 10.2 namely HEC-GeoHMS and HEC-GeoRAS. The HEC-GeoHMS enabled the team to delineate the watershed and the river network using the 5-m IFSAR DEM within the GIS environment. A total of 102 sub-watersheds were delineated within the main watershed. The team then proceeded with the series of flood simulation runs and generating of hydrograph based on the land cover map from Sentinel 2, soils map, and the localized rainfall and river velocity data from June 5-6, 2018 event. HEC-HMS and HEC-RAS are a suite of computer models consisting of several equations, thus, the presentation of such in this report is unnecessary (Castro and Maidment, 2020). The modeler did the calibration to fit the simulated and observed hydrographs by adjusting the model parameters (Sarchani and Tsanis, 2019; Wang *et al*., 2018). These parameters include the recession constant, ratio-to-peak, and Manning's n-values with the adjusted values of 0.4, 0.3, and 0.05, respectively, set as the final inputs for the main watershed. The other parameter number is specific to 102 sub-watersheds. Therefore, the average values of 78.81, 25.23, 1.44, 1.84, and 0.0125 for the curve number, initial abstraction, storage coefficient, time of concentration, and the initial base flow, respectively, are presented for the main watershed. Finally, the research team had evaluated the model performance by comparing the simulated and observed values using the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), root mean square errors-observations standard deviation ratio (RSR), and percent bias (PBIAS) statistics (Melaku *et al*., 2020). The calibrated flood model was the input in the hydraulic modeling phase to produce the 2D model domain map for the Solana watershed. The activity flowed the details of the 2D model development employed from the previous study's procedures (Santillan *et al*., 2016). This involves utilizing a delineated 2D flow area that represents the floodplain of the Solana river (Fig. 2). The 2D flow area consists of boundary conditions, namely the flow hydrographs indicating the inflows where discharge from the upstream starts to flow, the stage hydrograph at the river outlet considering the tidal boundary condition data in the Macalajar Bay, and the precipitation boundary condition. The delineated break lines across the river were also added indicating the abrupt changes in elevation such as the riverbanks and roads. The LiDAR DEM incorporated with actual riverbed information using bathymetric burning from field survey was the model simulation's primary input file. Using the bathymetric burned DEM, the simulated discharge will flow considering the river bed's elevation, improving the water volume estimations along river and floodplains of the watershed (Siev *et al*., 2016). Also, Manning's roughness coefficient values of specific land cover had influenced the simulated flood extent and depth of the hydraulic model.

The team validated the accuracy performance of the Solana 2D hydraulic model through ground cross-examination using field data associated with the simulated flood according to a particular historic rainfall event. A field validation survey was conducted through individual interviews from the locals, either flooded or not flooded, using predetermined random points within the floodplain.

Flood hazard map generation

The values of the calibrated and validated hydrograph developed in the hydrologic modeling component were then used as an input in the hydraulic modeling phase to generate a hazard map detailing the extent and depth of flood for the six return periods corresponding to 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year scenarios. The simulation of the six return period flood scenarios was based on the long historical rainfall intensity duration frequency (RIDF) obtained from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA). The final flood hazard index map consists of three categories according to flood depth such as low (<0.50m), medium (0.50m to 1.50m), and high (>1.50m).

Feature extraction and flood exposure analysis

The extraction procedure used the digital surface

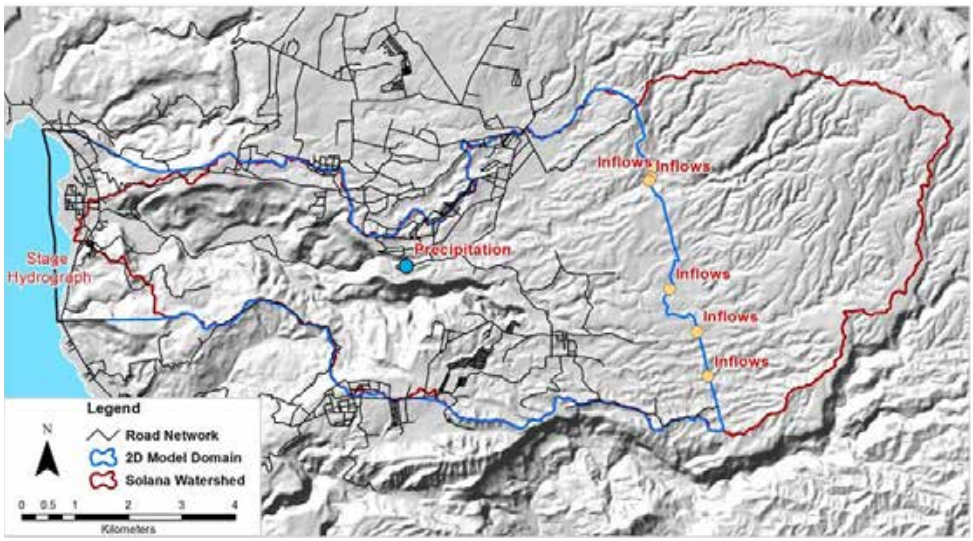


Fig. 2: Boundary conditions in the 2D model domain in Solana watershed.

model (DSM) component of LiDAR DEM data to manually extract the LULC features within the flooded surface. DSM is a type of elevation data that specifies LULC and other artificial features on the ground. High-resolution satellite images from Google Earth and Google Street View from the internet were also utilized as additional map layers in the feature extraction process, particularly in areas not covered by DSM. Validation of manually extracted features was done through geotagging activity of the identified and attributed LULC. The attributed LULC map was then used for the final risk exposure analysis of the 2D flood model domain of the watershed. Finally, the flood exposure analysis was through the cross-tabulation method of the exposed LULC according to the six return period flood scenarios.

RESULTS AND DISCUSSION

Land use/land cover map

The LULC map (Fig. 3) map of the Solana watershed generated using an object-based SVM algorithm obtained a higher accuracy based on the training sample points and validation sample points from the ground. The evaluation was made through confusion matrix analysis using the two sets of sample coordinate points from the ground validation survey and the satellite image, respectively (Xu *et al*., 2020). The confusion matrix analysis for the predicted and observed LULC classes revealed the producer accuracy values of 95, 83, 82, 89, 89, 100, 70, 100, 72, 93, 70, 100, 70 percent and the user accuracy values of 83, 94, 83, 96, 99, 100, 95, 100, 70, 93, 100, 71, and 100 percent for the open/cultivated, isolated trees, coconut, pineapple, buildings, banana, mango, water, tree plantation, road, shrubland, rice, and grassland, respectively. The analysis obtained an 88.05% overall accuracy. Table 1 shows the details of the land cover distribution by area. The flooded infrastructures, namely building and road comprise about 1.59% and 0.46%, respectively. As shown, open/cultivated land is the dominant land cover of the area, suggesting that more than half of the watershed is agriculturally active for crop production. Open/cultivated soil indicates that the Solana watershed is prone to flooding as the surface runoff accumulates quickly and flushes into the rivers and floodplains due to the removal of the protective forest cover (Bhattacharjee and Behera, 2018).

Calibrated and validated flood model

Flow routing and flood modeling for the watershed utilized the discharge time-series data from June 5 to 6, 2018, with a peak of 4.32 m^3/s (Fig. 4). The total precipitation relative to the observed peak discharge was 36.2 mm, with a maximum of 10.2 mm per 10-minute interval. These values served as inputs in calibrating the hydrologic model of the Solana watershed. Fitting the observed and simulated

Table 1: LULC distribution in the watershed

LULC	Area (ha)	% of the Total
Open/cultivated	4153.06	61.38
Isolated trees	1058.93	15.65
Coconut	948.61	14.02
Pineapple	257.37	3.80
Building	107.46	1.59
Banana	50.32	0.74
Mango	42.19	0.62
Water	35.63	0.53
Tree Plantation	32.33	0.48
Road	30.89	0.46
Shrubland	26.94	0.40
Rice	15.06	0.22
Grassland	7.58	0.11
Total	6,766.37	100.00

discharge values yielded a satisfactory result with a coefficient correlation of 86% (Fig. 5). The overall model calibration performance obtained a very good statistical agreement between the simulated and observed values with NSE, RSR, and PBIAS of 0.75, 0.50, and -5.77, respectively, implying acceptable model results. These findings indicate that the simulated flood behavior is as good as the observed flood from an actual event. Moreover, the model could generate different flood events using any rainfall scenario with an 86% accuracy level. Thus, the model is technically acceptable to generate flood hazard index maps at six different return period scenarios from any hypothetical and real rainfall events.

The historical rainfall event of tropical storm Sendong, internationally known as Washi in 2011 was the benchmark for the validation survey in coordination with the localities within the Solana watershed. However, due to the unavailability of Sendong rainfall data from the Solana watershed, the process interpolated the historical data from six PAGASA stations, namely Butuan, Lumbia, Malaybalay, Cotabato, General Santos, and Davao weather stations containing the rainfall record of Sendong for the flood model simulation and evaluation. Fig. 6 shows the simulated flood depth and flood extent based on the Sendong event at the Solana watershed. Flood extent covered the north of the 2D model domain outside the Solana watershed which is approximately 700 meters away from the main Solana river. This observation implies that some communities were still affected by floods during torrential rains even when they are at a certain distance away from the river.

Flood hazard map for the six return periods

Fig. 7 shows the 6-return period scenarios flood hazard maps from the calibrated and validated HEC-RAS model. The 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return periods of flood events would mean a 50%, 20%, 10%, 4%, 2%, and 1% likelihood of recurrence within a year, respectively (Apollonio *et al*., 2020). The basis of choosing the six return period scenarios was the recurrence of floods in the area, which is almost every year. The number

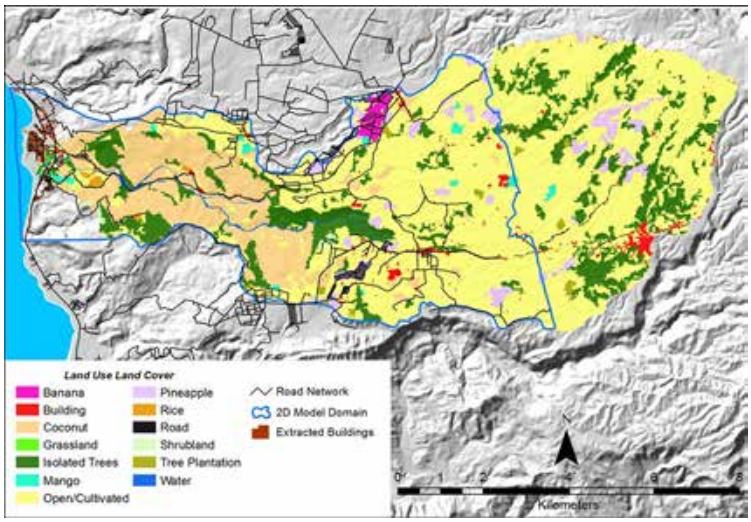


Fig. 3: Land use land cover map of Solana watershed

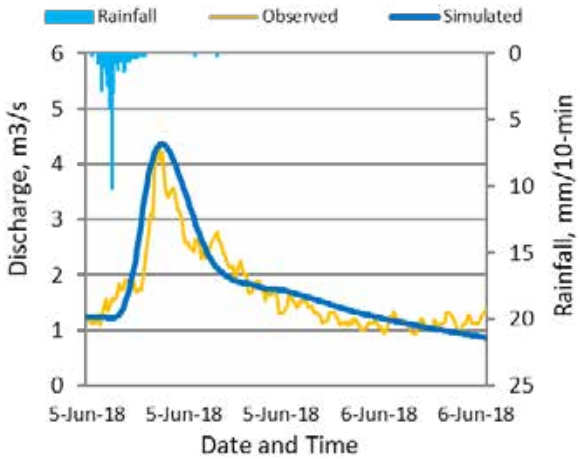


Fig. 4: Hydrograph for observed and simulated discharge data

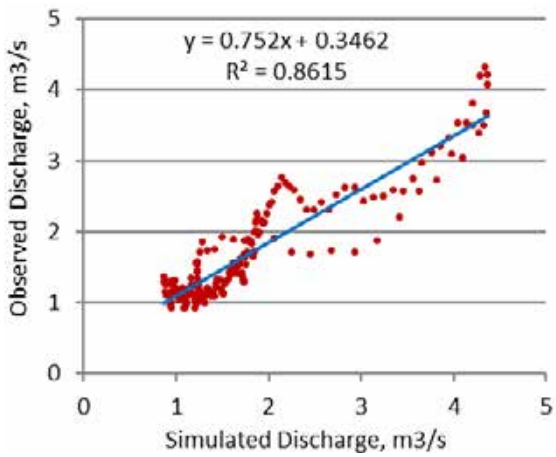


Fig. 5: Correlation between observed and simulated discharge data

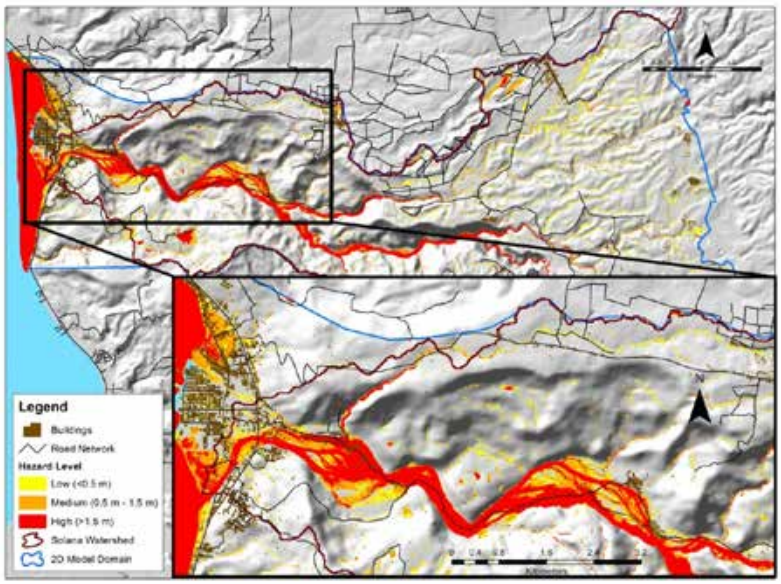


Fig. 6: Flood hazard map of 2011 tropical storm Sendong in Solana watershed

of years in the scenario was chosen arbitrarily. The generated flood hazard maps for the six return period scenarios conformed with the other studies showing the apparent increases of flooded areas with the delay of the return period (Shrestha and Lohpaisankrit, 2017). Fig. 7 depicts that the areas susceptible to flooding are mostly near the river, extending towards the floodplain of the watershed. These areas have the most affected households because of the increasing population. Additionally, the infrastructures that critically define the growing local economy are within these areas. Thus, the study site is highly vulnerable to flood hazards. This study underscores that flood modeling and hazard map generation is a helpful initiative for flood risk exposure analysis. Results of such analysis are vital in reducing and mitigating the impact of flood hazards in an urbanizing Solana watershed (Sharif *et al*., 2016).

Flood exposure analysis

The analysis yielded a total of 5,467 extracted buildings within the 2D model domain of the Solana

watershed, with the risk exposure of 22.0% to low, medium, and high levels of flood hazards during the 2-year return period scenario. This percentage of exposed land use or buildings had continuously increased with the succeeding chances of flood recurrence, maximizing 56.1% during the 100-year return period scenario (Fig. 8). This finding would mean that 78% of the buildings were initially not exposed to flood hazards during the 2-year return period. However, this percentage was reduced to 43.9%, implying that the exposure of the building to flood hazards would increase by more than half during the 100-year return period scenario. For the low level (<0.5m depth) flood risk, about 11.6% of the buildings were exposed during the 2-year return period and increased to 16.4% during the 100-year return period. Increases of the exposed structures for the compared scenarios were also evident for

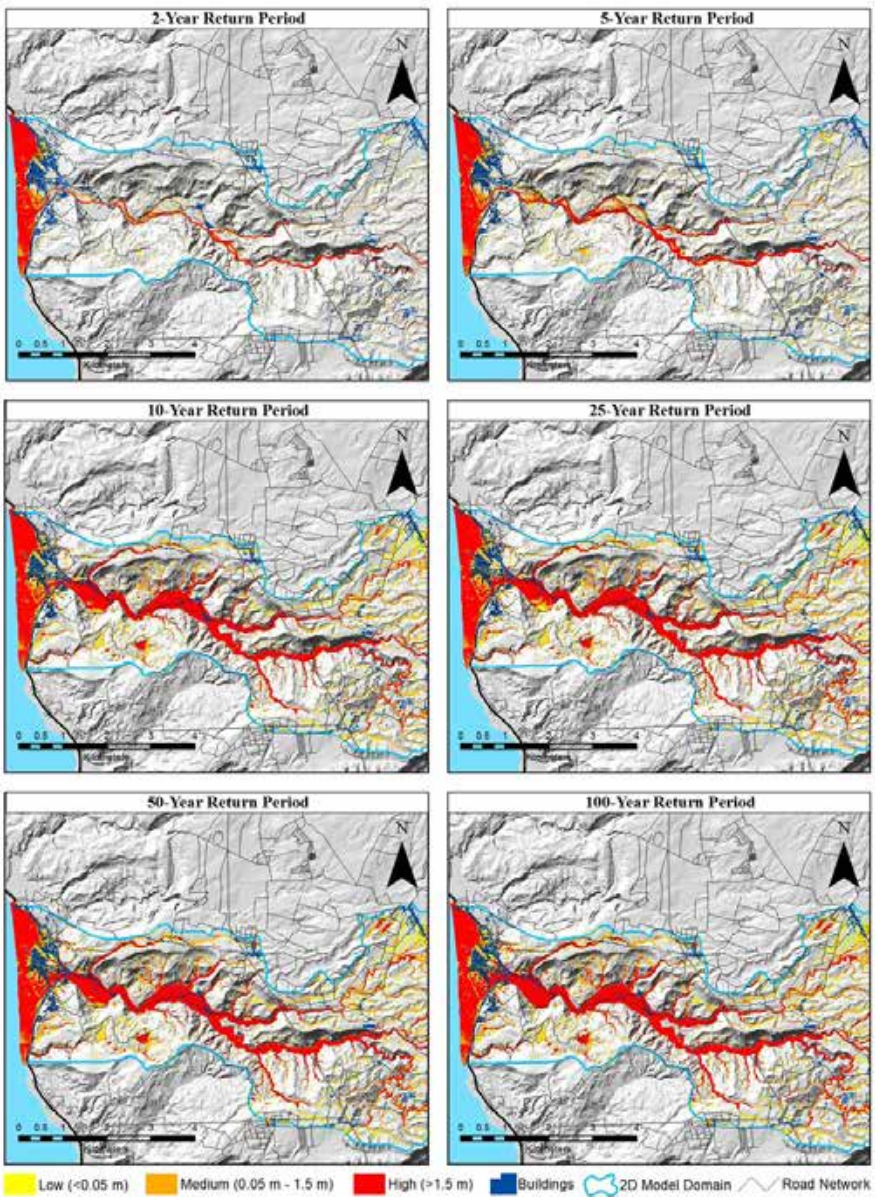
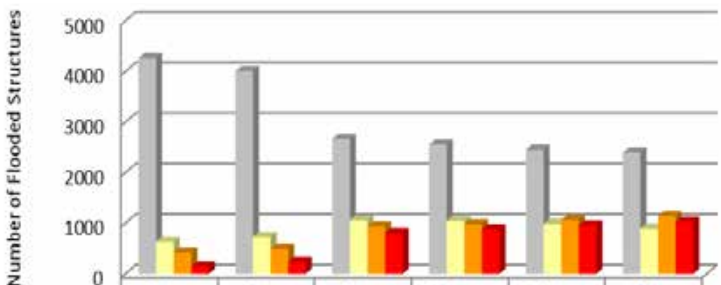


Fig. 7: Flood hazard maps in Solana watershed for the six return period scenarios.

both the medium (0.5m-1.5m) and high (>1.5m) flood levels. The cross-tabulation analysis shows an increasing pattern of exposed buildings as the return period covers a longer duration, and as the level of flood hazard reduces. However, some discrepancies of the pattern were obvious such as the cases of 50-year and 100-year return periods where the number of exposed structures had increased from low to medium risk level (Fig. 8). A similar increasing pattern and discrepancies of flood risk exposure of infrastructure across the return period were also revealed from previous studies (Apollonio *et al.*, 2020).

Fig. 9 shows the different land cover, including the road being exposed to flooded risk under the 1.50m depth for the six return period scenarios within the 2D flood model domain. The most extensive affected land cover was coconut, which is consistently higher in the six return period scenarios because it covers almost the watershed floodplain. Tree plantation, mango, and banana are the least exposed as they are usually occupying high-elevated sites. Table 2 presents a summary of the inundated land cover for the six return period scenarios. Cross-tabulation analysis of results shows an increasing pattern of percent risk exposure based on the total by return period scenarios (Table 3). The increase of flood risk exposure of various LULC is also reported from previous researches for 25-year, 50-year, and 100-year floods recurrences (Shrestha and Lohpaisankrit,



	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
Not flooded	4265	4006	2666	2556	2455	2398
Low	633	732	1061	1049	990	897
Medium	421	492	934	979	1065	1143
High	148	237	806	883	957	1029

Fig. 8: Flooded structures in Solana watershed for the six flood scenarios at different hazard levels

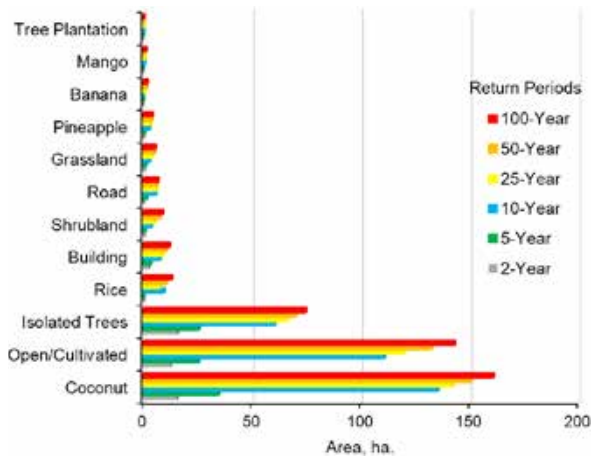


Fig. 9: Land use/land cover in Solana watershed exposed to flood hazard

Table 2: Percentage (%) of flood risk exposure by total across land cover

Land Cover	Return period scenarios					
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
Coconut	31.3	36.6	39.6	38.7	37.5	37.1
Open/Cultivated	25.8	27.0	32.4	32.6	33.0	33.0
Isolated Trees	31.7	27.1	17.7	18.0	17.5	17.2
Rice	0.6	0.5	2.9	2.1	2.7	3.0
Building	5.5	3.7	2.3	2.5	2.7	2.8
Shrubland	1.7	1.0	1.1	1.5	1.9	2.1
Road	0.5	1.9	1.7	1.7	1.6	1.6
Grassland	1.9	1.3	0.9	1.2	1.3	1.3
Pineapple	0.9	0.8	0.9	1.0	1.0	1.0
Banana	0.0	0.0	0.0	0.3	0.4	0.5
Mango	0.0	0.0	0.2	0.3	0.2	0.3
Tree Plantation	0.0	0.0	0.1	0.1	0.1	0.1

Table 3: Percentage (%) of flood risk exposure by total across return periods

LULC	Return period scenarios					
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
Coconut	2.5	5.4	21.2	22.2	23.5	25.2
Open/Cultivated	2.4	4.7	20.4	22.0	24.3	26.3
Isolated Trees	5.1	8.2	19.3	21.1	22.4	23.9
Rice	0.7	1.1	23.1	18.4	25.6	31.1
Building	6.0	7.7	17.0	19.7	23.1	26.4
Shrubland	3.0	3.5	14.0	19.4	27.8	32.2
Road	1.0	6.5	21.6	22.7	23.1	25.1
Grassland	4.7	6.1	15.5	20.6	25.7	27.5
Pineapple	2.8	4.8	18.9	22.1	25.1	26.3
Banana	0.0	0.0	0.6	24.2	34.3	40.9
Mango	0.2	0.2	20.3	23.1	23.0	33.3
Tree Plantation	0.2	0.4	19.8	24.6	26.2	28.9

2017). This result suggests that the longer the return period, the more hazardous the flooding scenario is.

Among the identified economically significant land cover in the area include rice and pineapple. Cross-tabulation analysis of results shows that the flood risk exposure of rice in percent for the six return period scenarios starting from the 2-year flood, had increased by a magnitude of 1.5, 31.9, 25.5, 35.3, and 42.9 for the 5-, 10-, 25-, 50-, and 100-year flood scenarios, respectively. Similarly, the flood risk exposure of pineapple had increased by a magnitude of 1.7, 7.7, 7.8, 8.9, and 9.3 for the considered flood scenarios, respectively. Unlike other perennial crops such as trees, coconut, and mango, rice and pineapple are vulnerable to damage when frequently exposed to flood hazards for a longer duration. Hence, decision-makers must prioritize these crops in terms of proper LULC planning and zoning to mitigate the negative impact of flood hazards on crop production in the future. The results also suggest identifying appropriate sites for built-ups and climate change-proof road designs to minimized flood exposure of these key features of the local and national economy.

CONCLUSION

The study enabled the application of HEC-HMS and HEC-RAS with the integration of advanced GIS and remote sensing technologies to develop a 2D flood model for risk exposure analysis and assessment of LULC within the Solana watershed. Emphasized in the study was the use of high precision RTK-GPS and high-resolution LiDAR-derived DEM. The method also included the use of a digital instrument such as a river velocity meter, deep gauge, and rain gauge through AWS in the gathering of rainfall and river discharge data for model development, calibration, validation, and evaluation. The study generated the flood hazard maps for the six return period scenarios. The research

team successfully calibrated the model with an 86% correlation between the observed and simulated discharge. The model input LUCL map of the watershed generated from the sentinel-2 satellite images with an accuracy level of 88.05% based on the confusion matrix analysis, showed that the open/cultivated land is the dominant land cover with 61.38% of the total area indicating high susceptibility to flooding. The study successfully analyzed the flood exposure of the various LULC of the site based on the generated flood hazard maps for the six return period scenarios. The result of exposure analysis showed that coconut plantation was the most affected LULC having 31.3% and 37.1% across the 2-year and 100-year return period scenarios, respectively. The least affected land covers were timber and fruit tree plantation because they are generally at higher elevations. Results also showed the increasing exposure of rice fields and pineapple plantations to flood hazards by a magnitude of 42.9 and 9.3 across the 2-year and 100-year scenarios, respectively. These crops have high economic potential, but highly vulnerable to flood damage when exposed to flood hazards for a longer duration. Thus, local and national authorities need to prioritize these crops in terms of appropriate LULC zoning and planning to minimize the negative economic impact of flood hazards. The model also produced maps that capture a densely populated settlement within the floodplain of the watershed, indicating high-risk exposure and vulnerability of such communities to flood hazards. This study emphasizes the identification of appropriate sites for built-ups and the development of climate change proof road designs based on the findings. Furthermore, the decision-makers must identify the strategic location of the evacuation center with safe access roads as recommended for more effective flood risk management within the urbanizing study watershed. This study also anticipates that the policy-making authorities must take advantage of the information in the challenge of creating a flood-resilient human settlement.

AUTHOR CONTRIBUTIONS

G.R. Puno spearheaded the research project, wrote the manuscript, prepared the GIS databases, thematic map layers, layout design, and graphs. R.C.C. Puno generated the land cover map using satellite images, performed the flood modeling activities, and edited the manuscript. I.V. Maghuyop did the logistics of the project operation and edited the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. Besides, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

2D	Two-Dimensional
BOA	Bottom of atmosphere
DEM	Digital elevation model
DSM	Digital surface model
PCIEERD-DOST	Philippine Council for Industry, Energy and Emerging Technology Research and Development-Department of Science and Technology
EMB-DENR	Environmental Management Bureau-Department of Environment and Natural Resources
ESA	European Space Agency
Geo	Geospatial
Geo-SAFER-Mindanao	Geo-Informatics for the Systematic Assessment of Flood Effects and Risks for a Resilient Mindanao
GIS	Geographic information system
ha	Hectare
GRVI	Green-red vegetation index
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center-River Analysis System
ISAR	Interferometric synthetic aperture radar
km	kilometer

LiDAR	Light detection and ranging
LULC	Land use/land cover
m	Meter
mm	Millimeter
NAMRIA	National Mapping and Resource Information Authority
NDVI	Normalized difference vegetation index
NIR	Near-infra red
NSE	Nash-Sutcliffe efficiency
PAGASA	Philippine Atmospheric, Geophysical, and Astronomical Services Administration
PBIAS	Percent bias
R^2	Coefficient of determination
RGB	Red, green, and blue
RIDF	Rainfall intensity duration frequency
RSR	Root mean square errors-observations standard deviation ratio
RTK-GPS	Real-time kinematic-global positioning system
SNAP	sentinel application platform
SVM	Support vector machine
TIFF	Tag image file format
TOA	Top of atmosphere
UP DREAM	University of the Philippines Disaster Risk and Exposure Assessment for Mitigation

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ORIGINAL RESEARCH PAPER

Cyanide ion oxidation by catalytic effect of nickel ferrites activated carbon composites

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ABSTRACT

BACKGROUND AND OBJECTIVES: Cyanide is a commonly-used substance in the gold recovery processes due to its high affinity for forming complexes with the precious metal, but inadequate handling and its final arrangement can lead to severe environmental contamination. In this context, this research focuses on the preparation of nickel ferrite-activated carbon catalysts for catalytic oxidation of cyanide ion in the presence of air.

METHODS: Hydrated salts of nickel ($Ni(NO_3)_2 \cdot 6H_2O$) and iron ($Fe(NO_3)_3 \cdot 9H_2O$) were used as precursors. The preparation pathways of ferrite and of ferrite-activated carbon composites were hydro-chemical with oxalic acid ($C_2H_2O_4$) and co-precipitation with sodium hydroxide. The parameters evaluated for catalyst preparation were Ni/Fe molar ratios (1/1.5 and 1/2), calcination times and temperatures (2-4 h/600-900°C), and ferrite-activated carbon mass ratios in the case of composites (1/1, 1/2 and 1/3).

FINDINGS: Oxidation results showed that the ideal Ni/Fe molar ratio was 1/2, and the calcination time was 4 h at 600 and 900°C for co-precipitation and hydro-chemical pathways of nickel ferrites, respectively. The catalyst that showed the greatest capacity for cyanide transformation was that obtained by the hydro-chemical pathway with oxalic acid, achieving efficiencies of 96.3% oxidation of cyanide ion. It was also determined that the largest impregnation of ferrite on the carbonaceous surface was 52.6% through the treatment with oxalic acid, with which the composite was obtained with the best catalytic properties of cyanide ion.

CONCLUSION: Nickel ferrite is able to oxidize cyanide ion to cyanate ion; being the ferrite-activated carbon combination, with which composite materials with catalytic properties of cyanide ion are obtained. Because of this, the materials studied could be applied in the detoxification of cyanurate solutions from metallurgical processes.

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INTRODUCTION

Sodium cyanide (NaCN) is a feedstock widely used in gold extraction through hydro-chemical paths due to their chemical affinity. However, it becomes a significant pollutant when the effluents generated in such metallurgical processes are not handled properly downstream. This is because they cause known impacts to surrounding flora and fauna (Kuyucak and Akcil, 2013). NaCN is also identified as a toxic substance that is capable of generating hydrogen cyanide at pH levels below 9.4 (Stavropoulos *et al.*, 2013). At industrial scale, several processes have been developed and implemented for cyanide removal. Moreover, several water treatment methods add strong oxidizing agents such as hydrogen peroxide (H_2O_2) and Caro's acid (H_2SO_4+H_2O_2) in order to counteract the pollutant effect of cyanide. However, both oxidizing agents are usually expensive alternatives that are required in significant amounts (Teixeira *et al.*, 2013a; Teixeira *et al.*, 2013b). The development of effective and recyclable catalysts for the cyanide oxidation process has been a relevant area of development. Several authors have reported suitable alternatives from activated carbon (Halet *et al.*, 2015; Kaušpėdienė *et al.*, 2017; Sivakumar, 2015), metal and activated carbon composites (Pesántez *et al.*, 2010; Singh and Balomajumder, 2016), biomass (Dehghani *et al.*, 2016), blends of iron, nickel, titanium and cobalt oxides (Kadi and Mohamed, 2015), and copper, nickel and cobalt ferrites (De la Torre *et al.*, 2018; Kariim *et al.*, 2020). As part of this trend, ferrite-based magnetic nanoparticles MFe_2O_4 (M: Ni, Zn, Mn, Cu) show several advantages, such as significant saturation magnetization, superparamagnetism, stability under high frequency conditions, and chemical and mechanical durability, among others (Hung and Thanh, 2011). Trevorite, for instance, is a rare type of spinel with a considerable nickel content with the chemical formula $NiFe_2O_4$. This compound is commonly reported in meteorites rather than terrestrial environments (O'Driscoll *et al.*, 2014). Their nanoparticles are reported to have adsorbent properties due to their biocompatibility. Moreover, they are characterised by strong paramagnetism and adsorption capacity, low toxicity and relatively ease of preparation. Inverse spinel structured $NiFe_2O_4$ ferrite shows ferromagnetism originating from the magnetic momentum of antiparallel spins between the Fe^{3+} ions (located in the tetrahedral interstice) and the Ni^{2+} ions (located in the octahedral interstice). $NiFe_2O_4$ ferrite shows a large surface area and low resistance for mass transfer. Moreover, the magnetic behaviour of these nanoparticles is linked to their size (Zandipak and Sobhanardakani, 2016). The most common wet-pathway procedures for ferrite synthesis are thermal decomposition of proper precursors, hydro-chemical solvo synthesis, inverse micelle synthesis, polyol-assisted synthesis, non-aqueous sol-gel and co-precipitation (Diodati *et al.*, 2014; Hajalilou and Mazlan, 2016; Rafique *et al.*, 2016). In this research, two methods for obtaining Nickel ferrite were assayed: co-precipitation with sodium hydroxide and a hydro-chemical synthesis in a dissolution of oxalic acid. These approaches were defined by considering the following information: De la Torre *et al.* (2018) synthesised Copper and Cobalt ferrite composites supported in activated carbon, using Copper, Cobalt and Iron Nitrates. A factor of 2 was adopted for the molar Fe/Cu and Fe/Co ratios. Ferrites were obtained through precipitation with sodium hydroxide at pH levels above 7 through the generation of mixed oxides $NiO{\cdot}Fe_2O_3$ like the ones presented in Fig. 1. The precipitated compound was supported over activated carbon in 1:1 (mass proportion). Blends were treated at 750°C for 4 hours. The catalysts' effectiveness reached 98% in terms of cyanide oxidation over 8 hours with aeration.

Kadi and Mohamed (2015) prepared a $NiFe_2O_4$/TiO_2-SiO_2 nanocomposite with magnetic properties and catalytic activity for cyanide oxidation. The authors reported assays carried out with several dispersing solutions and oxide ratios. Among these alternatives, $NiFe_2O_4$ preparation at a molar Fe/Ni ratio of 2, 0.1 M oxalic acid as precursor and thermal treatment at 600 °C (Kadi and Mohamed, 2014) delivered the most promising results. Other relevant alternatives were SiO_2/$NiFe_2O_4$, ethanol/$NiFe_2O_4$, NH_3/$NiFe_2O_4$ and Ti/ethanol at 0.03, 20, 1 and 0.8, correspondingly. The synthesized catalyst reported 100% cyanide removal after 1 hour of assay. It is important to mention that ferrites have a low solubility in cyanide solutions due to their refractory properties. The maximum dissolution capacity is approximately 4 % for Copper, Nickel and Cobalt and 1 % for Iron, considering the initial mass of metals (Rojas and Bustamante, 2007). Nickel ferrite ($NiFe_2O_4$) in contact with an aqueous solution of cyanide causes the catalyst to act as a reversible oxygen carrier, which allows the cyanide to

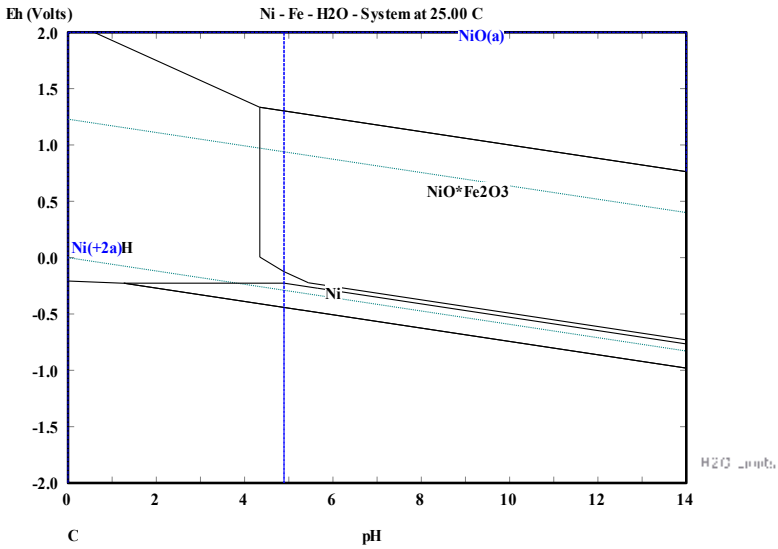

Fig. 1: Eh-pH diagram for Ni-Fe-H_2O at 25°C, molar ratio Fe/Ni=2

be oxidized to cyanate. At the same time, the catalyst can be regenerated at the moment it captures oxygen from the air to return to its original state (Kuo *et al.,* 2013). Likewise, activated carbon adsorbs molecular oxygen, which reacts with functional groups to form hydrogen peroxide, and this in turn oxidizes the cyanide ion (De la Torre *et al.,* 2018). In this research, the main objective was the study of the oxidation of cyanide by catalytic action of nickel ferrite-activated carbon composites. For this, it was necessary to evaluate the parameters involved in the preparation of nickel ferrites by both hydro-chemical and co-precipitation pathways, followed by impregnation of these ferrites on granular activated carbon, and catalysts that were evaluated through cyanide oxidation kinetic assays in order to measure their catalytic efficiencies and recyclability in the cyanide solution purification process. The experiments and analysis were done in the extractive metallurgy laboratory of the Escuela Politécnica Nacional (The National Polytechnic University) in Quito, Ecuador in 2019.

MATERIALS AND METHODS

In this research, the preparation of ferrite-based catalysts was through the hydro-chemical pathway with oxalic acid ($C_2H_2O_4$, analytical grade 98%, Acros Organics) as a precursor and through the co-precipitation pathway with sodium hydroxide (NaOH, analytical grade 97.0-98.8%, Fisher Scientific).

Nickel ferrites preparation

Hydro-chemical pathway with oxalic acid (OA)

In order to obtain Ni^{+2} and Fe^{+3}, Nickel Nitrate hexa-hydrated ($Ni(NO_3)_2 \cdot 6H_2O$, analytical grade 98.5%, Taian Health Chemical Co. Ltd.) and Iron Nitrate nona-hydrated ($Fe(NO_3)_3 \cdot 9H_2O$, analytical grade 98.5%, Taian Health Chemical Co. Ltd.) were used. The catalysts' preparation assays were carried out with molar Ni/Fe ratios of 1/1.5 and 1/2. Salts were added to 100 mL of OA at 1 M of concentration. The blending process was performed on a magnetic stirrer hot plate at 300 rpm and 80°C for 3 hours. After this stage, the blends were dried at 110°C for 24 hours. Once the moisture was removed, the samples were taken to an oven for their thermal activation. The process started at ambient temperature and reached 750°C with a heating slope of 12.5°C/min. The maximum temperature was for during 4 hours after it was reached. The remaining soluble compounds were removed through washing. This was done with 100 mL of sulphuric acid at 2% v/v (H_2SO_4, analytical grade 96.6% w/w, Fisher Scientific). Afterwards, a drying stage (110°C for 12 hours) was included. With the previous tests, once the best Ni/Fe molar ratio was defined, the same one with which the highest oxidation of the cyanide ion was achieved, the conditions of 600, 750 and 900°C were tested to establish the effect of the calcination temperature on

the preparation of ferrites.

Nickel ferrite preparation through the co-precipitation pathway with sodium hydroxide (SH)

This process required the salts to be dissolved in 300 mL of a sodium hydroxide (NaOH) solution 0.4 M with stirring at 500 rpm and ambient temperature. Also, the addition of a basic solution of 20% w/v NaOH was added until a pH level of 7 was reached. The stirring process was applied for 2 hours. Then, the solids were precipitated, filtered, and washed several times with deionized water. The solids had a slurry consistency, and they were dried at 110°C for 24 hours. As it was considered for the hydro-chemical pathway, molar Ni/Fe ratios of 1/1.5 and 1/2 were assayed. The calcination process at 750 °C for 4 hours was also included. Calcinated materials were washed with 100 mL of sulphuric acid at 2% v/v (H_2SO_4, analytical grade 96.6% w/w, Fisher Scientific) and several times with deionized water. Afterwards, a drying stage (110°C for 12 hours) was also included. As in the hydro-chemical pathway, after achieving the best Ni/Fe molar ratio, the effect of the calcination temperature in the preparation of nickel ferrites was evaluated. The evaluated temperatures were 600, 750 and 900°C.

Nickel ferrites characterization

The synthetized materials that were obtained through both pathways were analysed with X-ray diffraction in order to determine their mineralogical phases (Bruker AXS model D8 Advance). Moreover, their elemental composition was determined with X–ray fluorescence (Bruker S8 Tiger).

Cyanide oxidation assays with Nickel ferrites

The cyanide oxidation tests consisted of performing aeration tests (air flow: 180 NL/h) to cyanurated synthetic solutions of fixed volumes (500 mL) of sodium cyanide (500 mg NaCN/L, analytical grade 95.0%, Merck). In addition, each batch included 15 g/L of catalyst and was stirred at 800 rpm for 8 hours. In each elapsed hour, fixed portions of 5 mL of solution were taken. Regarding the experimental conditions, it was carried out at ambient temperature, and a pH level of 10.5 was maintained during the assays by adding NaOH (20% w/v). Cyanide quantification was performed by titration with solutions of Silver Nitrate (4.33 g/L, $AgNO_3$ analytical grade 98.5%, Fisher Scientific) and Potassium Iodine (KI analytical grade 99.5%, LobaChemie) at 10% w/v as indicator. Likewise, dissolved oxygen was registered with a potentiometer (Central Kagaku Corp model CGS-5).

The oxidation kinetics were adjusted to a first order reaction. With this, it was possible to determine the reaction's kinetic constant. For this, it was necessary to perform a linear adjustment of the natural logarithm of the free cyanide concentration Ln[CN^-] versus time (t), as indicated in Eq. 1.

$$Ln\left[CN^-\right] = Ln\left[CN^-\right]_o - k*t \quad (1)$$

Ferrite/activated carbon catalysts preparation

Once the catalysts' preparation conditions were defined for the hydro-chemical pathway, ferrite: activated carbon (Calgon GRC 20) mass ratios of 1:1, 1:2 and 1:3 were assayed. In a more detailed manner, the corresponding amounts of $Fe(NO_3)_3 \cdot 9H_2O$ y $Ni(NO_3)_2 \cdot 6H_2O$ were dissolved in OA 1 M while adding granular activated carbon Calgon GRC 20 (obtained through physical activation of coconut shell, with specific area of 1058 m^2/g and mesh of 6x12 (1.68 mm – 3.35 mm granulometry, dp_{80}= 2.25 mm). Blends were initially stirred at 400 rpm for 1 hour at ambient temperature and then at 90°C for 2 hours in the second stage. Moisture was removed from composites through drying at 100°C for 24 hours. Soaked carbon was poured in capped cresols prior to thermal activation with the purpose of reducing combustion. The thermal activation started at ambient temperature and continued until conditions reached the ferrite preparation settings. The last stage consisted of washing activated composites with H_2SO_4 at 2% v/v (100 mL), followed by filtration and drying at 110°C for 4 hours. A similar procedure was applied to the catalysts prepared through co-precipitation. In this case, ferrite:carbon mass ratios of 1:1, 1:2 and 1:3 were assayed. Each batch of solids was blended with 300 mL of SH 0.4 M and an additional dissolution of NaOH 20% w/v until a pH level of 7 was reached. The blends were stirred for 1 hour at ambient temperature then heated at 90°C for 2 hours. In the following stage, the solids were precipitated, filtered and washed with deionized water. The following procedures, including drying and thermal activation, were done under the conditions found in the preparation of the ferrite by

co-precipitation that presented the highest oxidation capacities of the cyanide ion.

Catalysts characterization

Chemical characterization of activated carbon-based composites and of activated carbon was performed according to ASTM standards for activated carbon: moisture (Standard Test Method for Moisture in Activated Carbon (ASTM, 2017), volatiles (standard test method for volatile matter content of activated carbon samples (ASTM, 2014), ash and fixed carbon (standard test method for total ash content of activated carbon (ASTM, 2018). Physical characterization of ferrite-activated carbon composites was carried out through scanning electron microscopy (Vega-Tescan microscope equipped with an EDS Bruker X-ray analyser). And the surface area of the porous materials was performed by nitrogen physisorption (Quantachrome NovaWin analyzer).

Cyanide oxidation assays with ferrites: activated carbon catalysts

The composites obtained through both mechanisms were assayed in oxidation tests with the purpose of identifying the one with the most effectiveness. Each assay consisted in adding 15 g/L of catalyst to a fixed volume of 500 mL of NaCN (500 mg/L). Moreover, stirring and aeration was also included (800 rpm and 180 NL/h, correspondingly). A comparative analysis of the synergy between the obtained ferrite and activated carbon was also proposed. These assays used 15 g/L of activated carbon and the corresponding amount of Nickel ferrite impregnated on activated carbon. 10 mL aliquots were taken to determine the concentration of iron and nickel in solution by Atomic Absorption Spectrometry, in a Perkin Elmer AA300 spectrometer. In addition, a test was carried out using 15 g/L of granular activated carbon and aeration (180 NL/h), to assess the influence of the catalytic action of activated carbon without impregnation (De la Torre *et al.*, 2018). The tests were carried out in duplicate to evaluate the homogeneity/heterogeneity of the composites when they are subjected to the oxidation test, through the calculation of the standard deviation of the cyanide concentration at each sampling point.

Assessing catalyst recyclability

With the composite that presented the highest cyanide conversion, cyanide removal tests were performed with 4 catalyst cycles with the same conditions as indicated above.

RESULTS AND DISCUSSION

Cyanide oxidation by aeration action reaches 27% after 8 h (Fig. 2), but the combination of activated carbon and aeration oxidizes 43% of the initial cyanide. Continuous agitation and aeration cause

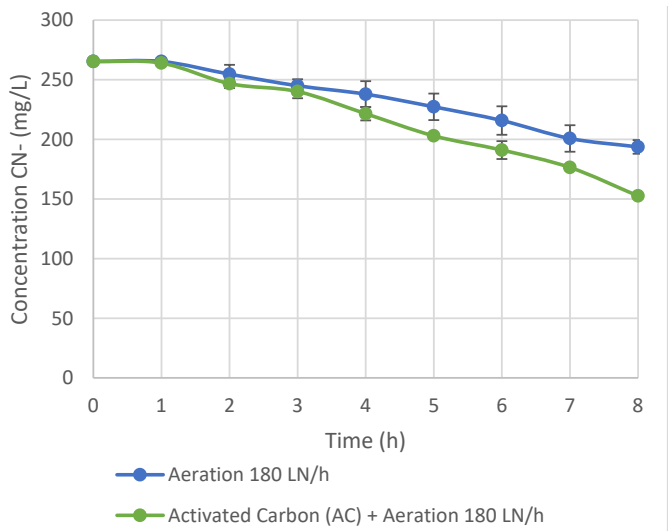

Fig. 2: Cyanide oxidation test with the presence of aeration and with the presence of activated carbon (15 g/L) and aeration, test time 8 h

cyanide ion to react with the supplied oxygen, as indicated in the next reaction Eq. 2 (Chen *et al.*, 2020; Pesántez *et al.*, 2010):

$$CN^-_{(aq)} + \frac{1}{2}O_{2(aq)} \leftrightarrow CNO^-_{(aq)} \quad (2)$$

On the other hand, the addition of activated carbon (AC) improves cyanide oxidation by 16%, a value that resembles that achieved by Dash *et al.* (2009) of 20% for granular activated carbon's action alone. With the above, the combination AC and aeration is considered able to oxidize twice as much cyanide as only activated carbon (Mudarra, 2017). The carbonaceous surface formed by the different functional groups reacts with molecular oxygen to generate hydrogen peroxide, which acts as an oxidizing agent of cyanide, as indicated in the next reaction Eq. 3 (De la Torre *et al.*, 2018; Tian *et al.*, 2015).

$$CN^-_{(aq)} + H_2O_{2(aq)} \leftrightarrow CNO^-_{(aq)} + H_2O_{(aq)} \quad (3)$$

Oxidation of cyanide ion with the use of nickel ferrites

The catalytic action of nickel ferrites ($NiFe_2O_4$) prepared by the two methods, (a) hydro-chemical pathway with oxalic acid (OA) and (b) by co-precipitation pathway with sodium hydroxide (SH), was evaluated. It is important to mention that the hydro-chemical method leads the Ni and Fe ions to meet Ni (+2) and Fe (+3) oxidation states at the moment of coming into contact with the oxalic acid solution, and when the dry mixture remains at high temperatures (600-900°C), the metals react to form mixed oxide ($NiFe_2O_4$). On the other hand, the preparation by co-precipitation causes the nickel and iron oxides to precipitate with the addition of sodium hydroxide solution, and then in the heat treatment, these reagents react to produce a spinel ($NiFe_2O_4$). With these two explanations, the ferrites obtained differ in their physicochemical, mineralogical, morphological and catalytic properties. That is why in this research, these two methods were evaluated in order to know the preparation conditions at which optimal catalysts for the detoxification of cyanide solutions are obtained.

Table 1 shows the mineral compositions of the different synthesized catalysts, as well as their elemental compositions (iron and nickel). Preliminary preparation of the catalyst by hydro-chemical pathway (OA) with calcination at 600°C for 2 h (OA R1/2 600-2h) obtains a compound with 44% trevorite (nickel ferrite) and 56% hematite (Fe_2O_3), but with the increase in calcination time to 4 h (OA R1/2 600), the composition of trevorite increases up to 70%. From these tests, it was determined that the optimal calcination time for obtaining nickel ferrites was 4 h. In addition, the influence of the calcination temperature was evaluated. In the case of the OA pathway with a molar Ni/Fe ratio of 1/2 ferrite preparation, by increasing the temperature to 750°C (OA R1/2 750) while maintaining the calcination time at 4 h, the composition of the ferrite increases by 10%; at 900°C (OA R1/2 900), it is increased by 8%.

Table 1: X-ray diffraction and x-ray fluorescence analysis of prepared ferrites

Preparation pathway	Theorical Ratio Ni/Fe	Calcination time (h)	Calcination temperature (°C)	Denomination*	Trevorite (%)	Hematite (%)	Ni (%)	Fe (%)	Ratio Ni/Fe
Hydro-chemical with oxalic acid	1/2	2	600	OA R1/2 600-2 h	44	56	22.08	52.67	0.42
	1/2		600	OA R1/2 600	70	30	21.21	49.00	0.43
	1/1.5		750	OA R1/1.5 750	82	18	26.17	43.91	0.59
	1/2		750	OA R1/2 750	80	20	19.87	52.56	0.37
	1/2		900	OA R1/2 900	78	22	21.41	50.59	0.42
Co-precipitation with sodium hydroxide	1/2	4	600	SH R1/2 600	99	1	17.87	49.18	0.36
	1/1.5		750	SH R1/1.5 750	99-100	-	23.07	45.89	0.50
	1/2		750	SH R1/2 750	99-100	-	19.06	48.12	0.40
	1/2		900	SH R1/2 900	99-100	-	19.69	49.00	0.40

*OA= hydro-chemical pathway with oxalic acid, SH= co-precipitation pathway with sodium hydroxide, R= molar ratio Ni/Fe

When the molar Ni/Fe ratio is 1/1.5 (OA R1/1.5 750), it is only improved by 2% compared to the 1/2 ratio (OA R1/2 750). Additionally, the experimental molar ratio of the samples must range from 0.37 to 0.59, when the theoretical ratio is 0.50. With the cyanide oxidation results shown in Fig. 5, the Ni/Fe ratios are defined, with which the highest efficiencies in the oxidation process are obtained. In the case of the SH pathway, catalysts with at least 99% trevorite were obtained in all preparations, as presented in Table 1, because in the precipitation process at pH greater than 7, mixed nickel and iron oxides were obtained ($NiO{\cdot}Fe_2O_3$), as shown in Fig. 1, according to Zhao *et al.* (2017). The molar ratios obtained ranged from 0.36 to 0.50. It is important to mention that molar ratios deviate from the theoretical value possibly to the dissolution of metals when acidic washing of catalysts was performed, where the color green was observed in the washing solutions. This phenomenon occurs due to the dissolution of nickel and iron oxides (De la Torre *et al.*, 2018).

The XRD patterns in Fig. 3 corresponding to the ferrites prepared by the hydro-chemical pathway show the presence of trevorite ($NiFe_2O_4$, nickel ferrite or nickel spinel) and hematite (Fe_2O_3). The characteristic peaks for trevorite are located at

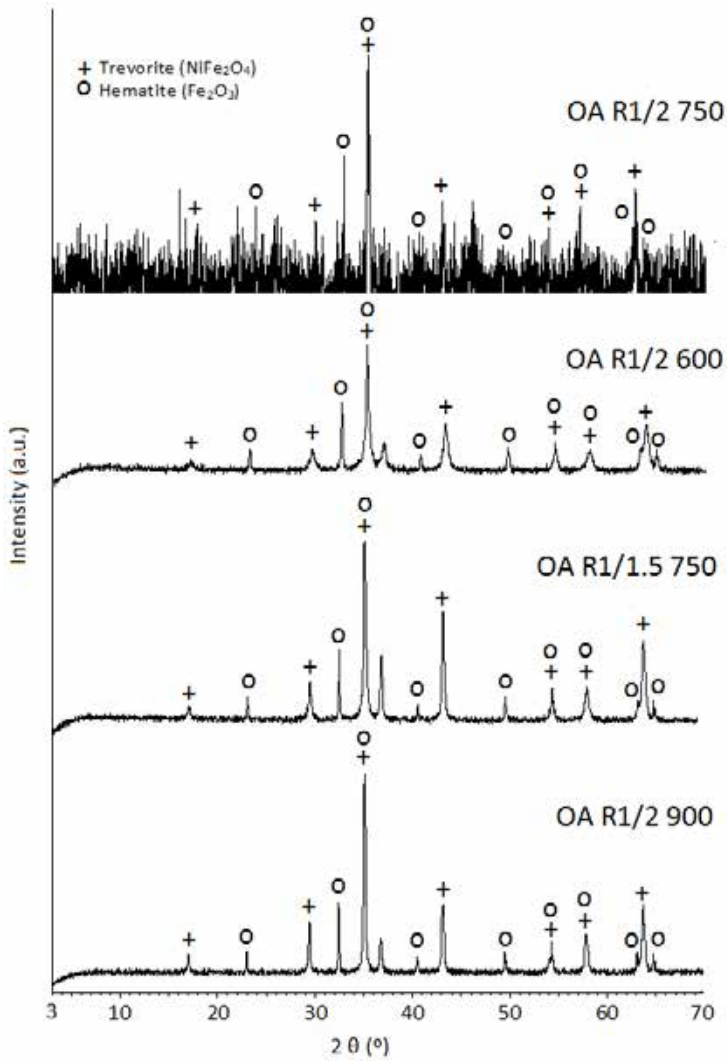

Fig. 3: XRD pattern of ferrites prepared by the hydro-chemical pathway

positions 18.37° (111), 30.28° (220), 35.66° (311), 43.31° (400), 53.78° (422), 57.34° (511) and 62.93° (440) (Livani *et al.*, 2018), and for hematite they are 24.14° (012), 33.24° (104), 35.61° (110), 40.81° (113), 49.47° (024), 54.09° (116), 57.62° (018), 62.46° (214) and 64.13° (300) (Basavegowda *et al.*, 2017). On the other hand, in the case of the ferrites prepared by the co-precipitation pathway (Fig. 4), all the XRD patterns present only trevorite peaks, which is why ferrites with purities greater than 99% are obtained.

With the catalysts shown in Table 1, cyanide oxidation tests were conducted to assess cyanide efficiency, with the results shown in Fig. 5A and 5B. Fig. 5A shows that OA R1/2 600-2h has a lower catalytic action than the other catalysts. This may be because this ferrite has the lowest percentage of trevorite. OA R1/1.5 750 has a linear trend, achieving an efficiency of 78% at the end of 8 h, whereas its similar OA R1/2 750 has a high oxidation capacity, achieving values like OA R1/1.5 750 in less than 3 h. In Fig. 5B, the catalyst with the least cyanide oxidation capacity is SH R1/2 750 unwashed, due to the presence of sodium that was not completely eliminated in chemical preparation and causes a ferrite with an amorphous structure to be obtained, which in turn is not active (Livani *et al.*, 2018). SH R1/1.5 750 had an efficiency of 56%, but its similar SH R1/2 750 reached 64% oxidation. From the results of Fig. 5, it is confirmed that with a Ni/Fe molar ratio of 1/2, a nickel ferrite is achieved with a crystalline structure with the highest catalysis capacities of the cyanide ion. In conclusion, it was confirmed that the best Ni/Fe ratio was 1/2 for both methods, which achieves the highest yield of nickel ferrite production

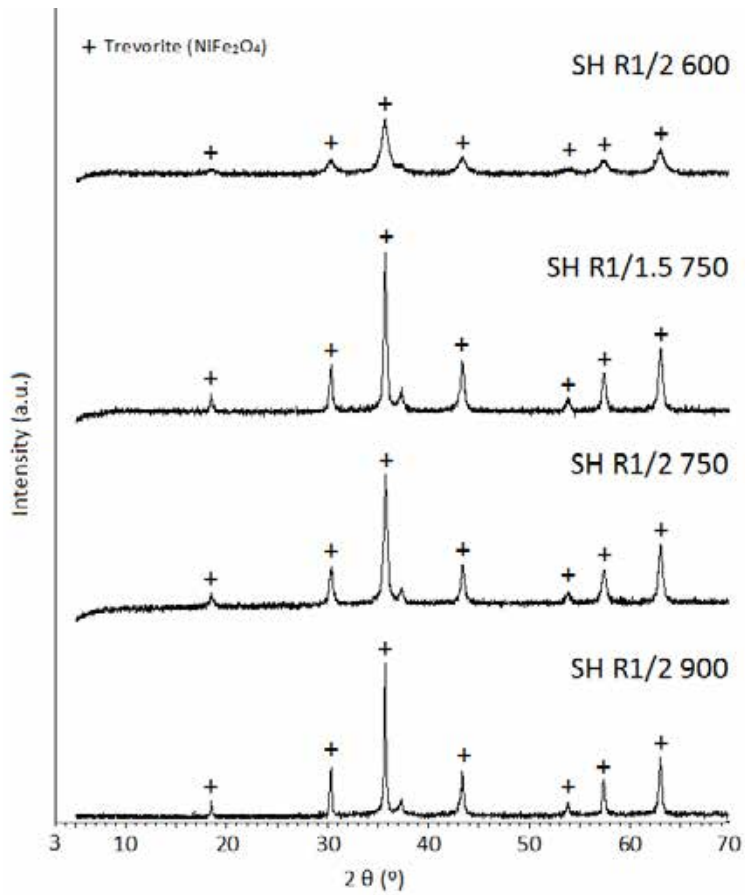

Fig. 4: XRD pattern of ferrites prepared by the co-precipitation pathway

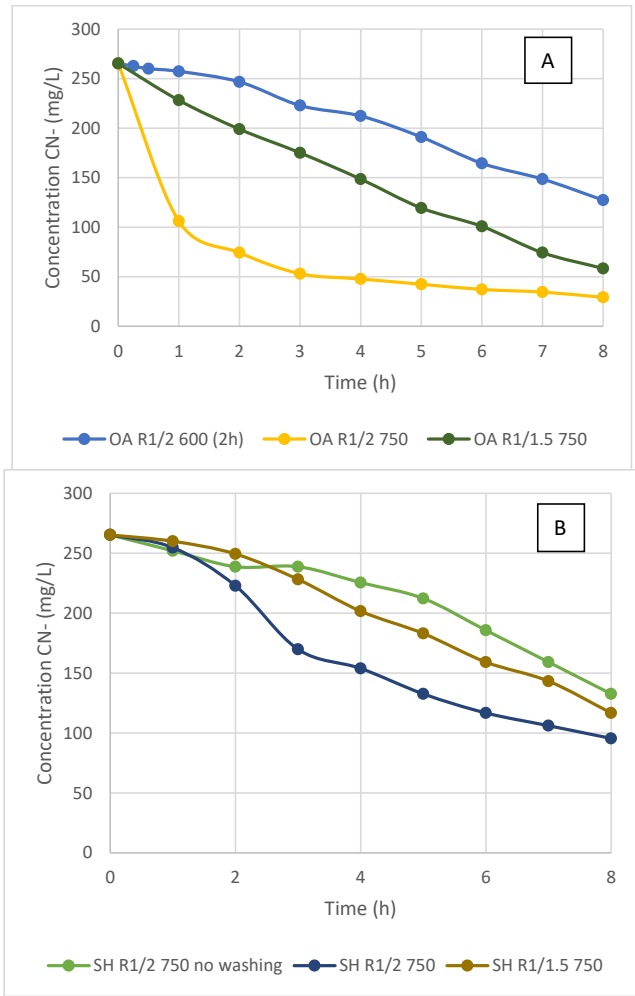

Fig. 5: Evaluation of the molar Ni/Fe ratio of ferrites prepared in the oxidation of cyanide ion (15 g/L, 180 NL/h, 5.5-8.5 mg O_2/L, 800 rpm). (a) Hydro-chemical pathway with oxalic acid (OA). (b) Co-precipitation pathway with sodium hydroxide (SH)

and higher oxidation of cyanide ion (Diodati *et al.*, 2014).

To understand the behavior of the curves presented in the graphs of Fig. 5, the kinetic constants and their reaction rates were determined, values that are indicated in Table 2. As can be seen, the kinetics of the reactions conform to a pseudo-first-order, as indicated by some authors who carried out the oxidation of cyanide with the use of ferrites (Guo *et al.*, 2018; Stoyanova and Christoskova, 2005). In the case of the hydro-chemical pathway, when evaluating the Ni/Fe ratio in the preparation of the catalyst, the ratio 1/2 (AO R1/2 750) is that with which a higher reaction rate is achieved and in turn the higher kinetic constant, in compared to the ratio 1/1.5 (AO R1/1.5 750). The same phenomenon occurs when comparing the reaction rates of the ferrites obtained by the co-precipitation pathway (SH R1/2 750 and SH R1/1.5 750), where the Ni/Fe ratio of 1/2 presents the highest reaction rate and the highest oxidation capacity of the cyanide ion.

From the results of Fig. 5, the influence of calcination temperature was assessed, as shown in Fig. 6A and 6B. In Fig. 6A, at a calcination temperature of 600°C, the compound OA R1/2 600 presented an efficient oxidation of cyanide after 1 h, after which the curve's trend becomes linear, achieving an efficiency of 85% at the end of 8 h.

At 750°C ferrite calcination, OA R1/2 750 achieves high oxidations until the third hour, after which the cyanide concentration remains almost constant with an efficiency of 89% at 8 h. Finally, the catalyst OA R1/2 900 obtained at 900°C had the highest catalytic activity among all the materials studied (95%), and therefore the higher cyanide oxidation reaction rate compared to the other catalysts, as indicated in Table 2. It is notable to see that, with the increase in the calcination temperature in the hydro-chemical preparation, the catalytic properties of ferrites were improved. In contrast, the co-precipitation pathway at the calcination temperature of 600°C achieved the catalyst SH R1/2 600 with greater oxidation efficiency of cyanide ion. On the other hand, with a heat treatment at 750°C (SH R1/2 750), ferrite decreases its catalytic capacity by 26%, compared to SH R1/2 600. Finally, with a calcination at 900°C, SH R1/2 900 showed the least catalytic activity, reaching a balance at the fourth hour. The catalytic activity of ferrites is based on the Mars-Van Krevelen redox cycle, where an oxygen atom migrates from the catalyst crystal network to the surface to be absorbed by cyanide and the oxidation reaction occurs; then, an oxygen from the aerated liquid phase replaces the vacancy from the migrated atom (Hirabayashi *et al.*, 2006; Kuo *et al.*, 2013). It was determined that the calcination temperature for optimal ferrite obtention by OA hydro-chemical pathway was 900°C, and for the SH co-precipitation pathway it was 600°C. At these temperatures, the impregnation tests of nickel ferrites on granular activated carbon were performed.

Oxidation of cyanide ion with the use of ferrite/ activated carbon composites

Fig. 7A and 7B show the oxidation kinetics of cyanide ion with the use of nickel ferrite-activated carbon composites obtained by the two methodologies. The catalyst prepared with a 1/1 mass ratio of ferrite by hydro-chemical pathway OA and activated carbon (R1/1 OA) had the highest catalytic capacity, with oxidation percentages of 96.3% (Table 4). From the proximate analysis it is observed that this compound contains the highest proportion of ash (52.56%, Table 3), equivalent to the ferrite impregnated on the surface of the carbon, so its oxidizing action was the highest reported, compared to the ratios 1/2 (R1/2 OA) and 1/3 (R1/3 OA). It is also evidenced that the mechanism of Mars-Van Krevelen takes place, where the oxygens of the ferrite migrate to the surface of the cyanide ion and achieve oxidation to ion cyanate (Hirabayashi *et al.*, 2006; Manova *et al.*, 2011).

It is estimated that approximately 4% of free cyanide formed complexes with dissolved nickel and iron during oxidation tests, which helps to understand that at least 92% effectively corresponds to the catalytic action of the composite in the oxidation of cyanide. The composite R1/2 OA, despite having 3% more ash content than R1/3 OA, showed a lower reaction rate than the latter (Table 4).

Fig. 7B shows the curves of the cyanide concentration over time through oxidation tests using catalysts of activated carbon impregnated with nickel ferrite prepared by the co-precipitation pathway. In all cases, it is observed that the final

Table 2: Parameters of the reaction kinetics of the prepared catalysts

Preparation pathway	Catalyst	Kinetic constant k (h^{-1})	Correlation coefficient (R^2)	Reaction Rate (mg/ L·h)	Cyanide oxidation (%)
-	Activated carbon	0.068	0.959	14.09	42.5
Hydro-chemical with oxalic acid	OA R1/2 600	0.197	0.937	28.19	85.0
	OA R1/1.5 750	0.186	0.981	25.87	78.0
	OA R1/2 750	0.230	0.832	29.52	89.0
	OA R1/2 900	0.345	0.979	31.51	95.0
Co-precipitation with sodium hydroxide	SH R1/2 600	0.249	0.965	29.85	90.0
	SH R1/1.5 750	0.103	0.957	18.57	56.0
	SH R1/2 750	0.138	0.983	21.22	64.0
	SH R1/2 900	0.056	0.741	13.27	40.0

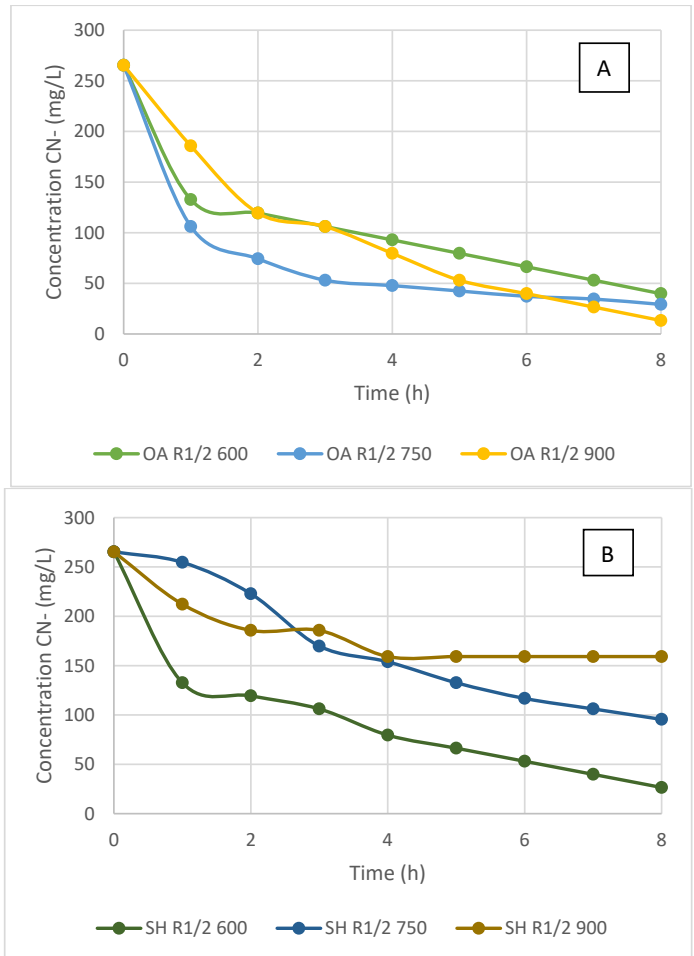

Fig. 6: Influence of the calcination temperature of prepared ferrites on the oxidation of cyanide ion (15 g/L, 180 NL/h, 5.5-8.5 mg O_2/L, 800 rpm). (a) Hydro-chemical pathway with oxalic acid (OA). (b) Co-precipitation with sodium hydroxide (SH)

concentration of cyanide (in the range of 139.3-152.6 mg/L) at the end of 8 h is similar for the 3 composites; so their reaction rates and kinetic constants have similar values (Table 4). Because the impregnations of ferrite by the co-precipitation pathway were less than 18.7%, the prepared composites do not have a good catalysis capacity of cyanide, which resembles that of activated carbon without impregnation. At the time of the calcination of the metal precipitate on the carbonaceous surface, the ferrite cannot be impregnated in a homogeneous manner, and the metal oxides formed agglomerates, which can be separated with the application of a magnetic field. The largest addition of nickel and iron achieved for these composite materials was 2.66% and 5.15%, respectively. On the other hand, in the case of OA composites, the salts used in impregnation manage to adhere by covering all the grains of the activated carbon, and at the time of calcination, the catalytic materials had greater affinity with the surface of the activated carbon.

Assessment of the recyclability of the ferrite/activated carbon composite

The reuse of the R1/1 OA composite was evaluated, as shown in Fig. 8A, as it is considered the composite with the highest percentage of cyanide ion oxidation. The initial composite showed a catalytic activity of 96%, and after the 4 consecutive cycles, it was 95, 90, 80 and 70%. One of the factors for the

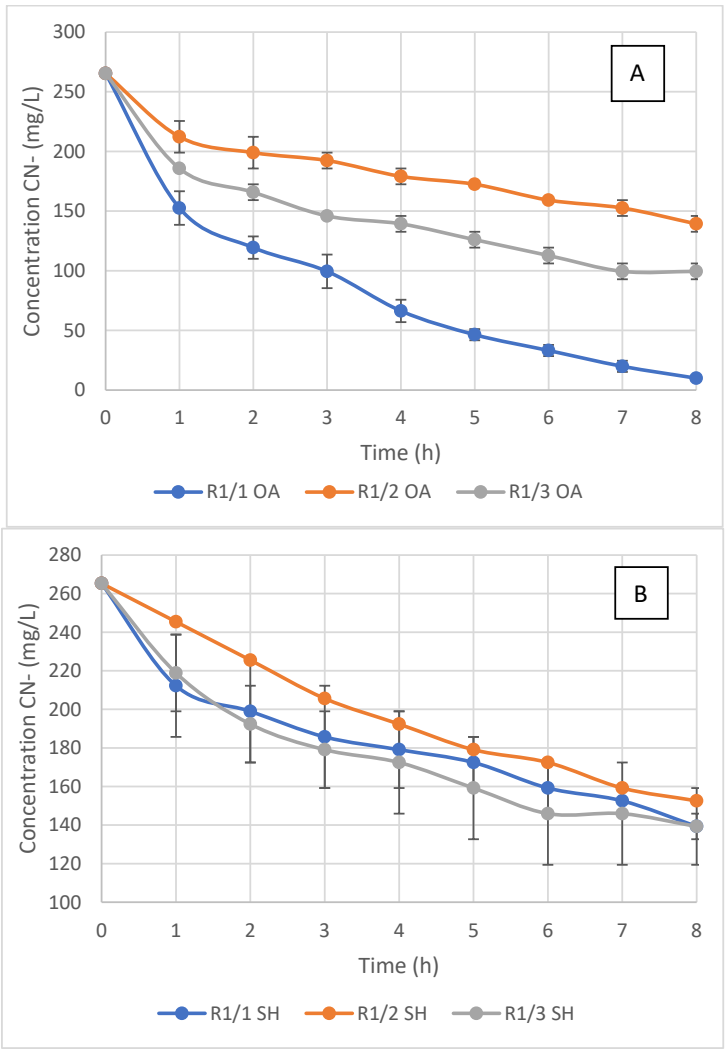

Fig. 7: Evaluation of the mass ratio nickel ferrite/activated carbon (Ratios 1/1, 1/2 and 1/3) in the preparation of catalysts and their influence on the oxidation of cyanide ion (15 g/L, 180 NL/h, 5.5-8.5 mg O_2/L, 800 rpm). (a) by hydro-chemical pathway (OA). (b) by co-precipitation pathway (SH)

Table 3: Proximate analysis of the composites obtained

Catalyst	Preparation pathway	Calcination temperature (°C)	Theorical mass ratio $NiFe_2O_4$ /AC	Real mass ratio $NiFe_2O_4$ /AC	Molar ratio Ni/Fe	Moisture (%)	Volatiles (%)	Ashes (%)	Fixed carbon (%)
Activated carbon	-	-	-	-	-	6.82	5.79	1.36	92.85
R1/1 OA	Hydro-chemical (OA)	900	1/1	1/0.9	0.61	1.82	10.57	52.56	36.88
R1/2 OA			1/2	1/4.8	0.47	2.15	7.87	17.65	74.48
R1/3 OA			1/3	1/5.9	0.63	2.11	8.06	14.82	77.12
R1/1 SH	Co-precipitation (SH)	600	1/1	1/4.3	0.49	4.99	10.99	18.72	70.29
R1/2 SH			1/2	1/100	1.11	3.02	6.39	1.44	92.18
R1/3 SH			1/3	1/50	0.66	2.02	6.45	2.17	91.38

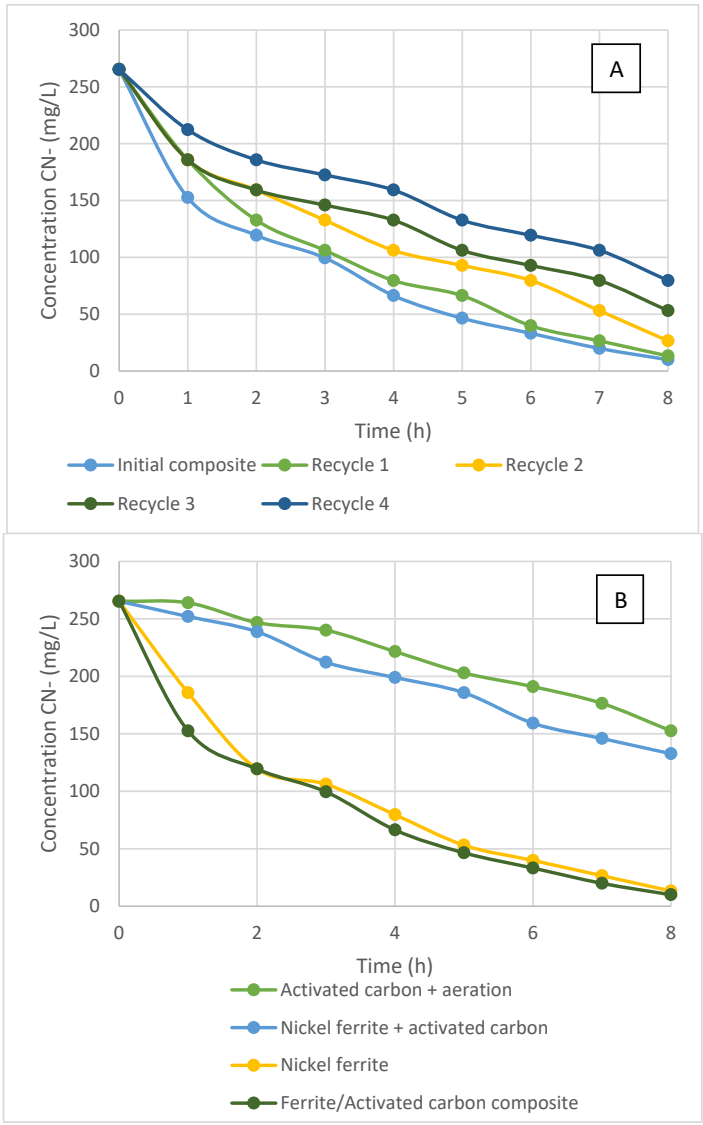

Fig. 8: Cyanide oxidation kinetics. (a) Recyclability tests of the R1/1 OA composite, (b) Comparison of catalysts studied. (15 g/L, 180 NL/h, 5.5-8.5 mg O_2/L, 800 rpm)

Table 4: Parameters of the reaction kinetics of the prepared composites

Catalyst	Preparation pathway	Kinetic constant k (h^{-1})	Correlation coefficient (R^2)	Reaction rate (mg/ L·h)	Cyanide oxidation (%)
R1/1 AO	Hydro-chemical (OA)	0.419	0.974	32.22	96.3
R1/2 AO		0.112	0.929	15.75	47.5
R1/3 AO		0.069	0.943	20.73	62.5
R1/1 SH	Co-precipitation (SH)	0.068	0.935	15.75	47.5
R1/2 SH		0.070	0.990	14.09	42.5
R1/3 SH		0.074	0.924	15.75	47.5

Table 5: Comparison of the oxidation capacities of the cyanide ion of different catalysts

Catalyst	Preparation	Cyanide oxidation (%)	Reference
Nickel ferrite ($NiFe_2O_4$)	Co-precipitation	85	Stoyanova and Christoskova, 2005
$NiFe_2O_4/TiO_2$-SiO_2 core-shell nanocomposite	Hydro-chemical	100	Kadi and Mohamed, 2015
Nickel ferrite (OA R1/2 900)	Hydro-chemical	95	This study
Nickel ferrite (SH R1/2 600)	Co-precipitation	90	This study
Nickel ferrite-activated carbon composite (R1/1 OA)	Hydro-chemical	96	This study

Table 6: Surface area BET, volume and pore diameter of the materials studied

Parameter	Calgon Activated Carbon	R1/1 OA	R1/1 SH
Surface area (m^2/g)	1058	610	1008
Volume pore (cm^3/g)	0.77	0.48	0.68
Radius pore (Å)	1.83	1.84	1.84

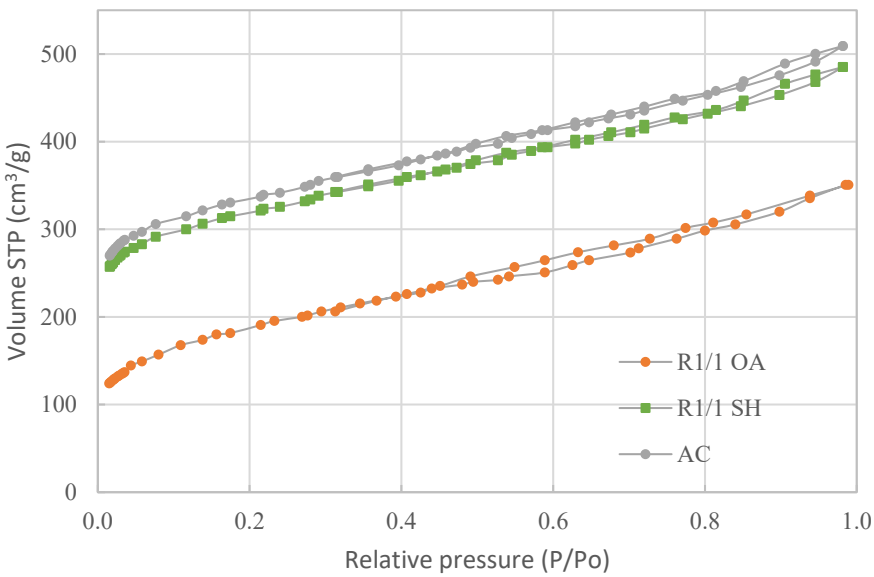

Fig. 9: N_2 adsorption-desorption isotherms of activated carbon and composites

catalytic activity decrease is that during agitation, some of the nickel dissolves in the cyanurate solution, with values ranging from 2.58, 0.92, 0.83, 0.52 and 0.31% Ni, corresponding to the cycles performed; on the other hand, the iron dissolved was less than 0.08% in all tests. The composites are also prone to erosion due to attrition during agitation (Marsden and House, 2006). When comparing the initial composite with the first cycle, it is observed that similar oxidation efficiencies were obtained, making it possible to assume that the dissolution of nickel does not contribute to the oxidation of cyanide. In addition, a comparative analysis was performed between the R1/1 OA, activated carbon (AC), ferrite ($NiFe_2O_4$) and the activated carbon and nickel ferrite mixture without impregnation, as shown in Fig. 8B. For this, the amount of nickel ferrite was taken from the ash percentage of R1/1 OA and the remaining amount corresponded to the AC. Activated carbon with aeration had the least catalytic action. Nickel ferrite

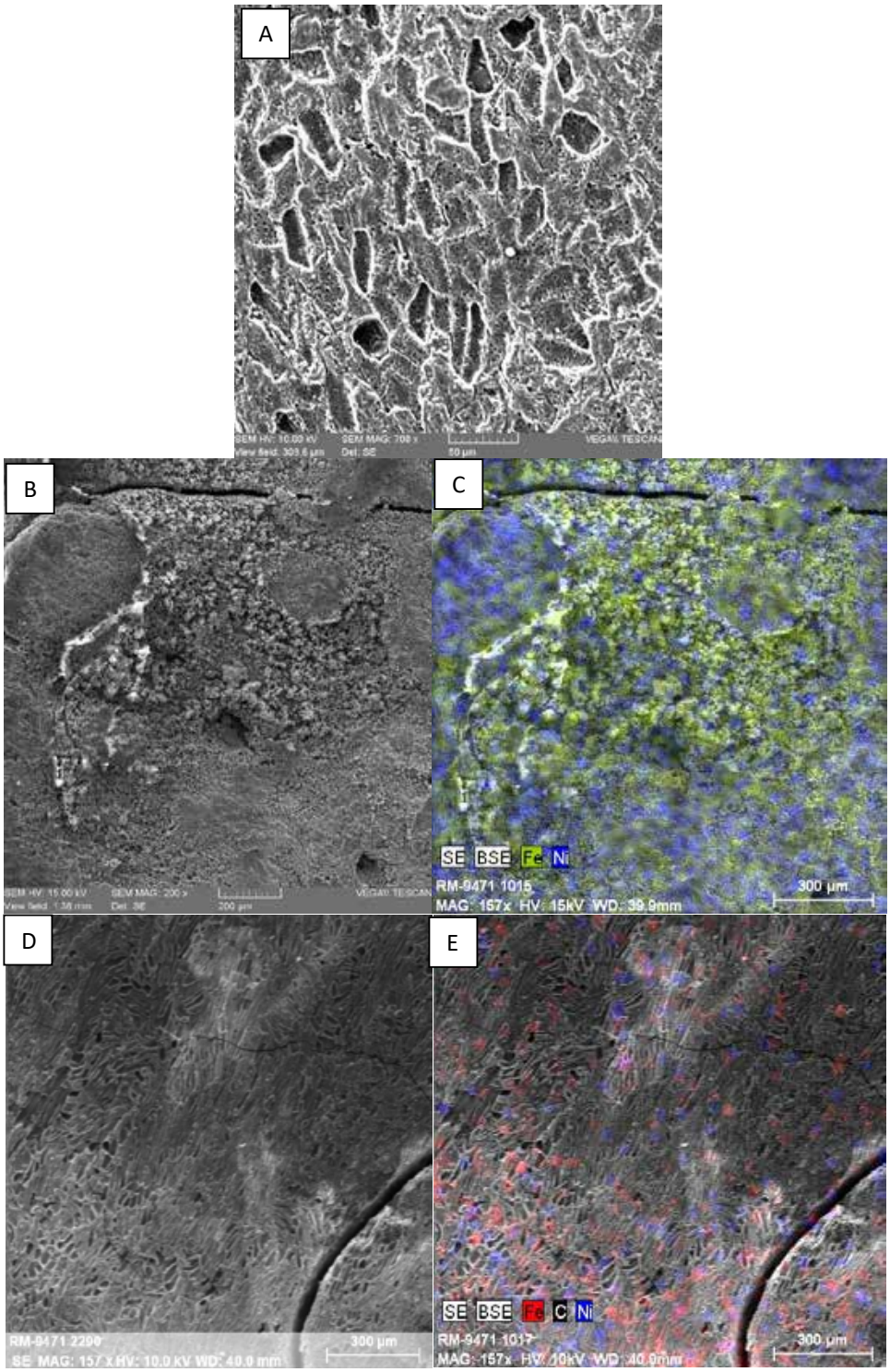

Fig. 10: Scanning electron microscopy images. (a) Activated carbon 700X, Composite R1/1 OA 157X: (b) morphological analysis, (c) elemental analysis by EDS, Composite R1/1 SH 157X: (d) morphological analysis, (e) elemental analysis by EDS

has a kinetics similar to the R1/1 OA composite. Also, it is observed that the AC and ferrite mixture without impregnation had lower oxidation capacity of cyanide compared to the composite, which makes it possible to show that the incorporation of the catalyst on the carbonaceous surface improves catalysis properties, as determined by De la Torre *et al.* (2018).

Table 5 shows a comparison of different nickel ferrite-based catalysts used in the oxidation of the cyanide ion. The nickel ferrite of this study obtained by the co-precipitation method has a higher oxidation capacity than that obtained by Stoyanova and Christoskova (2005). In this study, when working with calcination temperatures of 900°C, ferrites are obtained with a crystalline lattice with greater catalytic capacities than that obtained at 120°C by the mentioned authors. On the other hand, the core-shell nanocomposite ($NiFe_2O_4/TiO_2$-SiO_2) obtained by Kadi and Mohamed (2015) is capable of oxidizing 100% of the initial cyanide. This research achieves a similar value (95%) to that of the second mentioned authors.

From the comparative analyzes indicated, it is established that for this study, the catalyst that presented the best catalytic capacities was the composite of nickel ferrite impregnated in activated carbon, a material prepared by the hydro-chemical pathway in the medium of oxalic acid, Ni/Fe molar ratio of 1/2, calcination temperature of 900°C and ferrite-activated carbon mass ratio of 1/1. This catalyst was able to oxidize more than 96% of the initial cyanide ion, with a reaction rate of cyanide consumption of 32.22 mg/L/h and with a reaction kinetic constant of 0.419 h^{-1} ($6.98x10^3$/min).

Characterization of the composites

Table 6 shows the results obtained from nitrogen physisorption of activated carbon and prepared composites. Calgon activated carbon has the largest surface area. Following is R1/1 SH, a material that, having a higher proportion of fixed carbon and low impregnated ferrite content, has a porous surface that is not as affected. In contrast, R1/1 OA reduces its surface area by 42.3% compared to unimpregnated carbon, a percentage affected by the incorporation of calcined ferrite into the carbonaceous surface. In all cases, the pore radius is the same, so the pore size is not affected in the impregnation of nickel ferrites.

The nitrogen adsorption and desorption isotherms shown in Fig. 9, indicate that the 3 catalysts fit the type IV isotherms, according to the IUPAC classification, characteristic of mesoporous samples (*Li et al.*, 2017). In the case of the ferrite-carbon composite obtained by the co-precipitation method, the isotherms are similar to those of activated carbon, because this material does not manage to impregnate significant amounts of ferrite on the carbonaceous matrix and therefore, it is not seen to be affected the surface area of activated carbon. On the other hand, in the case of the composite prepared by the hydro-chemical pathway, due to the fact that significant amounts of ferrite are incorporated on the activated carbon, the carbonaceous surface is affected when the pores are closed by the presence of impregnated ferrite. Therefore, this last composite has a lower adsorption capacity; however, its catalytic properties of the cyanide ion are not altered by this phenomenon.

Through scanning electron microscopy analysis, the commercial Calgon carbon has a heterogeneous surface (Fig. 10A), from 700x magnification, the characteristic porosity begins to be observed, indicating a porous material. The R1/1 OA composite (Fig. 10C) shows homogeneity of the metals incorporated into the carbon surface. Also, it was found that in carbon fractures and slits, there are fragments of sintered ferrite as indicated by De La Torre *et al.* (2018). Finally, in R1/1 SH (Fig. 10E), mixed oxide is impregnated in parts where there is no porosity, so it is possible to observe macropores.

CONCLUSION

Nickel ferrites ($NiFe_2O_4$) synthesized by hydro-chemical and co-precipitation pathways had catalytic activity of oxidation of cyanide ion to cyanate. Mixed iron and nickel oxides with approximately 100% purity were obtained by the co-precipitation pathway with sodium hydroxide with oxidation efficiencies of 90%. It is important to mention that for this method, it is advisable to carry out several washes with water after the precipitation process in order to obtain ferrites with a high content of the pure species. On the other hand, by preparing the hydro-chemical pathway with oxalic acid, ferrites of 80% purity and oxidation efficiencies of 95% were obtained. These ferrites, due to their crystallization nature, presented the best catalytic oxidation activities of cyanide ion. The purity of these ferrites could be increased by varying the concentration of

oxalic acid when the process of dissolving nickel and iron salts is carried out; also, another influencing factor would be the increase in the calcination temperature during the heat treatment. Activated carbon and nickel ferrite composites were obtained. The hydro-chemical pathway achieved the highest impregnation of mixed nickel and iron oxide, with a maximum value reaching 52.6%; in contrast, with chemical preparation by co-precipitation, the maximum impregnation was 18.7%. This shows that ferrite/activated carbon composites obtained by hydro-chemical preparation with oxalic acid had the best catalytic properties of cyanide oxidation, with reported efficiencies of 96.3%. It should be taken into account that, during the calcination process, the salts and activated carbon mixture must be in covered or insulated containers in order to reduce the losses of carbonaceous material produced by combustion with the oxygen in the environment. Furthermore, recyclability tests of the nickel ferrite-activated carbon composite demonstrate that catalysts have high cyanide oxidation efficiencies (above 70%), but in each cycle, the catalyst loses effectiveness due to the deactivation of the ferrite crystalline structure. There is a noticeable difference when comparing the efficiency of the nickel ferrite catalyst impregnated in activated carbon to the ferrite and carbon mixture without impregnation, where the composite material has twice the catalytic capacity of cyanide ion than the mixture of ferrite and carbon without impregnation. Also, it is beneficial to produce composite-type catalysts as they are easy to handle, recover by sieving or magnetism, and are reusable. Moreover, the scanning electron microscopy of the composites showed uniformity in the distribution of nickel and iron metals on the surface of activated carbon grains, and it was also shown that catalyst fragments occupied the slits of the absorbent material. The materials studied are the basis for the search for new catalysts for the detoxification of cyanurate solutions produced in the mining industry.

AUTHOR CONTRIBUTIONS

C.Y. Feijoo performed the literature review, developed the experiments, analyzed and interpreted the data, prepared the manuscript text, and manuscript edition. E. De la Torre performed the literature review, designed the experiments, compiled the data and manuscript preparation. R.A.C. Narváez helped in the literature review 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.

ABBREVIATIONS

Å	Armstrong
AC	Activated carbon
°C	Celsius degrees
$C_2H_2O_4$	Oxalic acid
Co	Cobalt
Cu	Copper
CN^-	Cyanide ion
CNO^-	Cyanate ion
dp_{80}	Particle diameter with 80% of the accumulated through-hole
Eh	Redox potential
Fe	Iron
Fe_2O_3	Hematite
$Fe(NO_3)_3{\cdot}9H_2O$	Iron nitrate nona-hydrate
h	Hour
H_2O	Water
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
k	Reaction kinetic constant
L	Liter
m^2	Square meters
M	Metal

MFe_2O_4	Metal ferrite with oxidation state +2
mg	Milligrams
min	Minutes
mL	Milliliters
mm	Millimeters
Mn	Manganese
NaCN	Sodium cyanide
NaOH	Sodium hydroxide
NH_3	Ammonia
Ni	Nickel
$NiFe_2O_4$	Nickel ferrite/Trevorite
$Ni(NO_3)_2{\cdot}6H_2O$	Nickel nitrate hexa-hydrate
NiO	Nickel oxide
NL	Normal liters
O_2	Oxygen
OA	Hydro-chemical pathway with oxalic acid
OA R1/2 600	Nickel ferrite prepared by hydro-chemical pathway, molar Ni/Fe ratio of 1/2, 600°C temperature and 4 h calcination
OA R1/2 600-2h	Nickel ferrite prepared by hydro-chemical pathway, molar Ni/Fe ratio of 1/2, 600°C temperature and 2 h calcination
OA R1/1.5 750	Nickel ferrite prepared by hydro-chemical pathway, molar Ni/Fe ratio of 1/1.5, 750°C temperature and 4 h calcination
OA R1/2 750	Nickel ferrite prepared by hydro-chemical pathway, molar Ni/Fe ratio of 1/2, 750°C temperature and 4 h calcination
OA R1/2 900	Nickel ferrite prepared by hydro-chemical pathway, molar Ni/Fe ratio of 1/2, 900°C temperature and 4 h calcination
pH	Hydrogen potential
R1/i OA	Nickel ferrite-activated carbon composite prepared by hydro-chemical pathway, ferrite-carbon mass ratio of 1/i (i=1, 2 or 3)
R1/i SH	Nickel ferrite-activated carbon composite prepared by co-precipitation pathway, ferrite-carbon mass ratio of 1/i (i=1, 2 or 3)
rpm	Revolutions per minute
SH	Co-precipitation pathway with sodium hydroxide
SH R1/2 600	Nickel ferrite prepared by co-precipitation pathway, molar ratio Ni/Fe of 1/2, 600°C temperature and 4 h calcination
SH R1/1.5 750	Nickel ferrite prepared by co-precipitation pathway, molar ratio Ni/Fe of 1/1.5, 750°C temperature and 4 h calcination
SH R1/2 750	Nickel ferrite prepared by co-precipitation pathway, molar ratio Ni/Fe of 1/2, 750°C temperature and 4 h calcination
SH R1/2 900	Nickel ferrite prepared by co-precipitation pathway, molar ratio Ni/Fe of 1/2, 900°C temperature and 4 h calcination
SiO_2	Silica
Ti	Titanium
TiO_2	Titanium oxide
%	Percentage
%w/v	Percentage weight/volume
Zn	Zinc

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CASE STUDY

Solid waste management system for small island developing states

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ABSTRACT

BACKGROUND AND OBJECTIVES: Solid waste management which entails the generation, storage, collection, transportation, processing, treatment and disposal of waste products is regarded as a challenge to many countries worldwide. The focus and methods vary in all territories given the wide range of factors which influence waste management. Small Island Developing States face unique challenges which are influenced by their peculiar physical, economic, social, political and institutional characteristic. Consequently, they require a solid waste management system tailored to their unique requirements.

METHODS: Qualitative and quantitative data were gathered between February and November 2019 from various primary and secondary sources using the following instruments and techniques: literature review of reports, news articles, legislation, journals and case studies; on-site observations; and administering questionnaires in the study area in October 2019. The study area comprised 3 communities which were representative of the waste management district, and were selected using the purposive sampling method, while the sample size of 0.3% of the households in the study area was selected randomly by administering questionnaires to anonymous respondents in arbitrary households in the communities. Using descriptive methods, data was tallied and grouped, then the content analysed to determine patterns, to answer questions to the problems and to determine relationships and themes. Findings were summarised, simplified and presented in formats such as graphs and tables and written descriptive accounts.

FINDINGS: Solid waste management affects all countries irrespective of their level of development. The focal point varies across societies. Small Island Developing States have a unique challenge posed by their particular characteristics. Given that each territory has a peculiar mix of factors, any solid waste management system derived must be exclusive to each. There is no single, ideal system which can be proposed. Whatever the system decided upon, it must encompass the socioeconomic, cultural, economic, legislative, institutional and environmental context of the territory, but most of all it must be accepted by the majority of stakeholders.

CONCLUSION: A solid waste management system must be unique to each area, given that there are many dynamic variables which affect the system. Consequently, the system derived from this study can only be applied in its entirety to the study area. Other areas with similar characteristics can lend examples from the study area.

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INTRODUCTION

Solid waste management (SWM) is a critical infrastructural service which is integral to urban and environmental management worldwide (Sarkar and Singh, 2015). Like most other infrastructural services, it has come into sharp focus, since people are affected by the adverse impacts such as water and air pollution or overflowing landfills, forcing the responsible parties to address the problems of increased waste generation (Seadon 2010). In 2016, global annual waste generation was 2.01 billion tonnes of waste and, driven by rapid urbanisation and growing populations, the quantum is expected to increase to 3.4 billion tonnes over the next 30 years as indicated in the World Bank Report "*What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*" (Kaza *et al.,* 2018). The same authors purport that SWM is critical for sustainable, healthy, and inclusive cities and communities and so, is highly important. Notwithstanding its importance, developing nations, much like their developed counterparts experience challenges in implementing a SWM system given its very dynamic nature. Di Maria *et al.* (2017) emphasize the strong correlation between the SWM system and the economic context of a society. They compared the Umbria region in Italy and the West Bank in Palestine to contrast solid waste management in developed and developing countries. They concluded that in developed countries, an adequate legal and economic framework, economic sustainability and political stability were vital for successful solid waste management, while political instability, inadequate awareness and inadequate economic revenues resulted in poor SWM in the developing country. Guerrero *et al*. (2013) state that solid waste management is a challenge for authorities in developing countries mainly due to increased waste generation. Although an effective SWMS is important in promoting healthy communities, the myriad of issues faced by developing countries cause this notion to be neglected (UNEP, 2018). The challenges faced by Small Island Developing States (SIDS) are unique because they have the distinctive characteristic of not only being geographically small but also having physical and topographic constraints coupled with peculiar economic, social, political and institutional characteristics which greatly hinder their ability to establish and implement sustainable waste disposal options (Agamuthu and Herat, 2014). Mohee *et al.* (2015) observed that SWM is an ongoing problem in SIDS mainly due to the continuous increase in waste generation and the lack of effective and sustainable waste management strategies. As their lifestyles and economies continue to improve, their consumption and waste disposal patterns will continue to change radically (Shah *et al.*, 2019). Institutional limitations defined as a lack of policies and strategies on behalf of the government to promote SWM approaches are one of the main challenges of SIDS (Mohee *et al*., 2015). Some implications to developing countries of not having a system of enforcing legislations for solid waste management are the creation of an environment which enables open dumping and open burning of waste, the failure to implement best practices such as segregation and take-back obligations on recyclables and the inability to collect revenue through taxes or charges (Bundhoo, 2018). Hence, they constantly endeavour to derive creative solutions to their SWM problems. Therefore, a study to assess the institutional, legislative, economic and physical context of SIDS and examine current global best practices in SWM was conducted under the broad headings of waste generation, waste collection, waste treatment/disposal and waste management. The aim of this study was to derive and propose a solid waste management system which will address the problems of municipal (household) waste management in SIDS such as the lack of physical space for landfills and lack of adequate regulatory, legislative, socioeconomic, institutional and technical frameworks to foster effective waste management. The aforementioned issues resulted in environmental issues such as: increasing levels of imported non-biodegradable goods, decreasing water quality and overexploitation of natural resources (UNEP, 2019). Research was conducted in the waste management district of Gros Islet in Saint Lucia in 2019.

MATERIALS AND METHODS

Study area description

The waste management district of Gros Islet is 1 of 11 in Saint Lucia in the North America (SLSWMA, 2016). It registered population expansion of 20.8% and shows trends for favourable population expansion (CSOSL, 2011). It is located north of the capital city of Castries and offers commercial, touristic, residential, industrial, institutional and recreational services to the entire island. Therefore, it requires a suitable

SWMS which caters to these characteristics. In that regard, the study population comprising 3 representative communities from the district was selected. The communities are representative of the broad socioeconomic and physical development levels in the island i.e. suburban, urban and rural based on empirical observation and literature review. *Reduit* is a suburbanised residential area which is planned/organized, has paved streets, all structures enjoy street/curb frontage and a stable population of medium to high socio-economic class. It is located along the major road linking Gros Islet town to the capital -Castries City. *Gros Islet town* is the municipality head and an urban settlement with high population density, mixed socioeconomic groups and mixed residential and commercial activity and dynamic population where not all structures enjoy street frontage and are linked via footpaths. Although urbanised, development was haphazard/unplanned in certain sections. *Monchy* is a predominantly residential, rural area which displays potential for population increase in the near future as evidenced by the recently observed rise in advertisements for land for sale in the area as well as statistics from the Department of Physical Planning in Saint Lucia. Monchy also has varied socioeconomic groups and is a mixed land use community located away from major thoroughfares. Not all structures enjoy curb front or even motorable access. Fig. 1 illustrates the location of the study area in Gros Islet District in the island of Saint Lucia at coordinates 13.9094° N and 60.9789° W, showing the communities of Monchy, Reduit and Gros Islet Town from which the study population was selected.

Study design and data collection

Data was collected between February and November 2019 from a variety of primary and secondary sources of not older than 10 years. This helped to identify a study area and population, to determine the current SWM practices and situation in the study area, as well as to discover global best practices in waste management which could be applied to the study area. This included collection of information on the institutional, legislative, economic and physical context of waste management from desktop and literature reviews of reports, news articles, legislation journals and case studies, and where possible, on-site observation. The study population was selected using purposive sampling

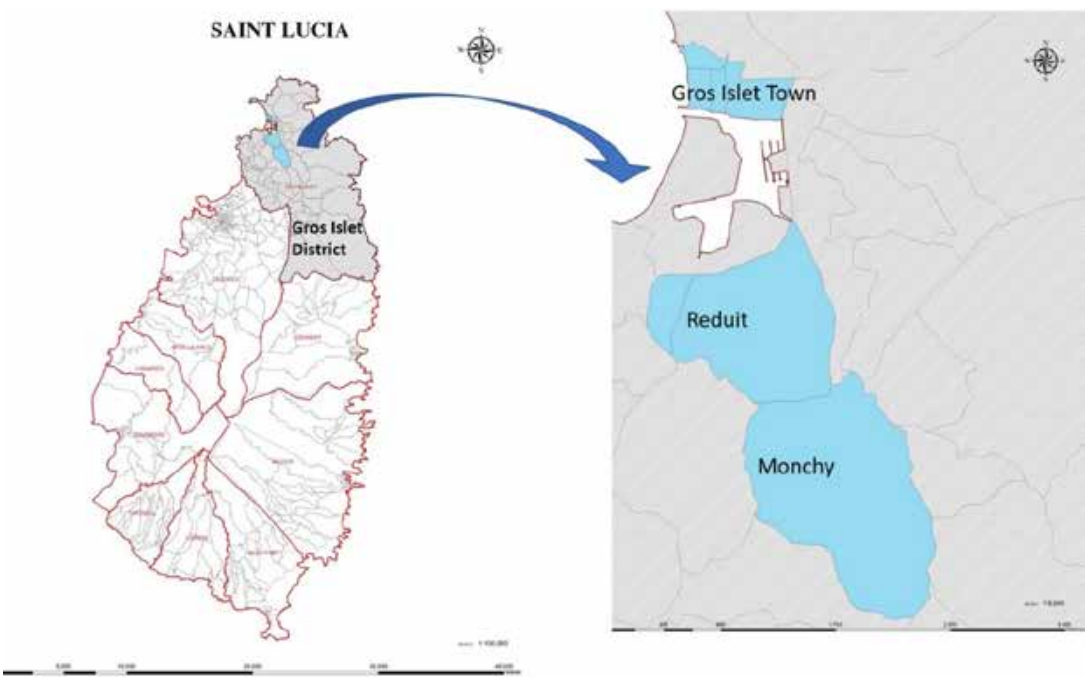

Fig. 1: Geographic location of the study area in district of Gros Islet in the island of Saint Lucia

(Gay *et al.*, 2009) since the subjects were selected from 3 different communities which were representative of the physical and economic development categories of the entire district. Questionnaires were randomly distributed in the study area in August 2019 to gather socioeconomic data on respondents (such as age, gender, education level, sector of employment, etc.), to discover respondents' perspectives, prejudices, limitations and attitudes to waste generation, collection, disposal, treatment and management. They comprised 2 open-ended, 11 closed-ended and 7 mixed questions. The mixed questions offered respondents a list of options including the "OTHER" option to allow them to express answers which may not have been in the list provided. They were administered in-person to 31 arbitrary households. Thirty of them were completed and returned. The unreturned questionnaire was not considered in the analysis. That is, 1 each from 10 households in each of the 3 communities studied. This constitutes approximately 0.3% of households in the study area or 0.1% of households per community. Although the sample size was small, responses were generally consistent among respondents. It should be noted that all United States Federal Government norms and ethics for conducting research involving human subjects as stipulated by the Institutional Review Board (IRB) were adhered to. Notwithstanding attempts to be fair in selecting a sample, sampling bias defined by Gay *et al.* (2009) as a sampling error caused by the researcher when some aspect of the sampling creates a bias in the data, may present itself. Some sources may be in the disparity in the microculture of the communities selected because the main criteria for selection of the sample were the predominant land use and level of urbanization. Consequently, practices and perspectives which would be affected by the culture of the community e.g. those based on the relationship among neighbours, the design of the community or socioeconomic status may be lost. Even so, any potential disparity is anticipated to have negligible effects on the results of the study.

Data analysis

The main variables analysed included the method of disposal, frequency of disposal, quantity of waste disposed, type of waste, administrative and social system and resident perspective on the aforementioned variables. Next, key strategies in descriptive data analysis for qualitative data were applied. These included analysing the content; identifying themes and patterns; asking key questions to understand the problem or context; organisational review to understand the organisation and aspects relevant to the problem; noting antecedents and consequences; displaying findings in a summarised, simplified, meaningful format such as charts, graphs, concept maps, figures, etc. and finally, stating what is missing or noting the questions for which no answer was found. From the findings gaps were identified and became the basis for recommendations which were used to propose a SWM system for the study area.

RESULTS AND DISCUSSION

Solid waste management in the district is not homogenous and is characterized by many challenges (SLSWMA, 2016). The Annual report of 2014/2015 (most recently published) indicated that the SLSWMA offers free, twice weekly, municipal solid waste collection and once monthly bulk waste collection to all communities on the island with the help of contracted waste haulers who gather waste curbside where possible, in communal bins or at collection point service where households cannot be accessed by the collection vehicle. All waste is disposed of at the national landfill. (SLSWMA, 2016). At the time of this study, SWM practices did not cater for segregation of waste at the source. Therefore, all waste was disposed of together. Several small businesses currently engage in material recovery but there is no approved framework for their operations, so activities are not standardised (SLSWMA, 2012 as cited in Te-HsinTsai, 2013). Generally, more females (60%) participated in the study, in which persons aged 51 and older accounted for most respondents. This occurred because at the time that responses were collected in Reduit, the persons available to respond were retirees. This however is not representative of the willingness to respond or the demographic character of the sample or study area. Most respondents (30%) had attained primary education as the highest level, however, persons had attained varying levels including university education. The employment characteristics were varied. i.e. public/ private sectors, self-employed, technical /administrative, managerial /non-managerial personnel. Retired persons accounted for 23% of

respondents. There were marked difference between the results for the 3 communities studied, supporting claims that SMW challenges very even between urban and rural areas (De Medina-Salas *et al*., 2020).

Waste generation

Most studies focus on the treatment and disposal of waste since the impacts of poor disposal are more immediately experienced. However, the amount of waste generated is as important as the disposal or treatment (Singh, *et al.,* 2018). Fortunately, emerging concepts of resource-efficiency and resource-recovery have shifted that focus (Lehman, 2010). Respondents ranked their communities as very clean in relation to waste management on a scale of 1 to 10. Forty-seven percent ascribed values of 10 or 8, while 20% ranked it at 9. There was no obvious relationship between the perceived cleanliness and education level attained or gender of respondents based on responses to the questions asked. However, male response was outstanding ranking cleanliness at 8 and 7, while females gave ratings of 10, 9, 6 and 4 (Fig. 2).

Using an average plastic grocery shopping bag with a capacity of 2-3 gallons (4-5 kg.) as a point of reference, respondents quantified the number of bags of household waste generated per week (Fig. 3). 47% of respondents disposed of approximately 4-7 bags of waste, while 43% disposed of 1-3 bags. The remainder disposed of 8-10 bags. Monchy stood out in the category of 1-3 bags per household while Gros Islet town did in the category 4-7 bags. UNEP (2019) revealed that the average SIDS inhabitant generates approximately 2.3 kg of waste per day while the

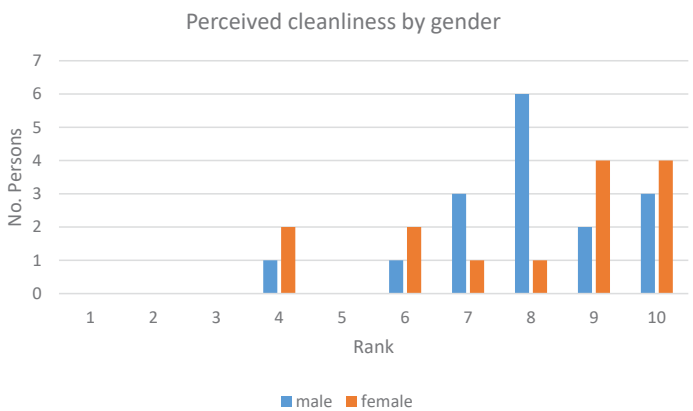

Fig. 2: Ranking community cleanliness by gender

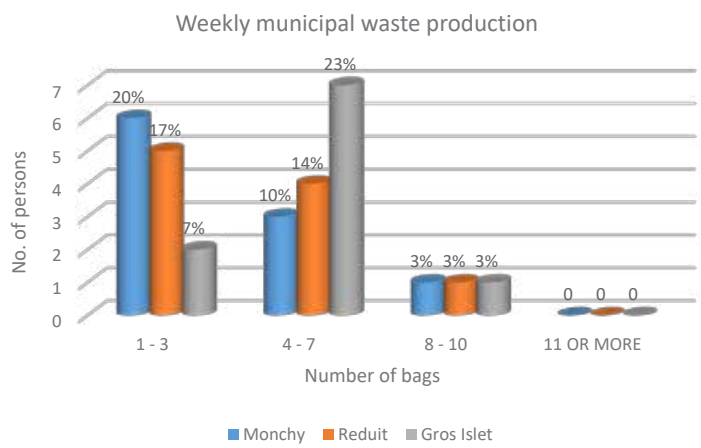

Fig. 3: Weekly municipal waste generation by community

global average is 1.55 kg.

The study did not consider the number of persons in the household, nor if the respondent was the head of the household. 37% of the respondents indicated that their consumption habits/patterns had changed to reduce the amount of household waste generated. Of these, 46% were 51 years and older and only 27% had attained university education as the highest level. Of those who had changed, 73% were from Gros Islet town. None of them were from Monchy (Table 1).

Finally, the comparison of responses by education level revealed that 37% of respondents who had not made any change had attained primary education as the highest means of formal education (Fig. 4).

The availability of free municipal waste collection service further exacerbated the issue of waste generation since it is convenient for residents to simply place their waste at the roadside for collection, at only the cost of carrying the trash out. Responses displayed in Table 1 indicate that there was little to no effort to reduce the quantity of waste generated through changed consumption habits. This observation is consistent with the SLSWMA (2018) report which confirmed that residential waste represents the largest component of the waste stream; and underscores the need for education and awareness-building initiatives. It should also be noted, that organic waste generally accounts for a higher percentage of the total waste generated (SLSWMA, 2018). Residents of Gros Islet town seemed to realize that waste generation could be better managed and were taking steps to do so through changed consumption patterns. This may be due to the urban nature of Gros Islet town where space constraints may have awoken respondents'

Table 1: Changed consumption patterns

		Total number of responses				
Category		Yes	%	No	%	Total
Age (years)	21-30	0	0	3	16	3
	31-40	2	18	3	16	5
	41-50	4	36	4	21	8
	51 +	5	46	9	47	14
Sub-total		11		19		30
Education level	PRIMARY	2	18	7	37	9
	SEC	1	9.5	4	21	5
	TEC/VOC	4	36	4	21	8
	UNI	3	27	2	10.5	5
	OTHER	1	9.5	2	10.5	3
Sub-total		11		19		30
Community	Monchy	0	0	10	53	10
	Reduit	3	27	7	37	10
	Gros Islet	8	73	2	10	10
Sub-total		11		19		30

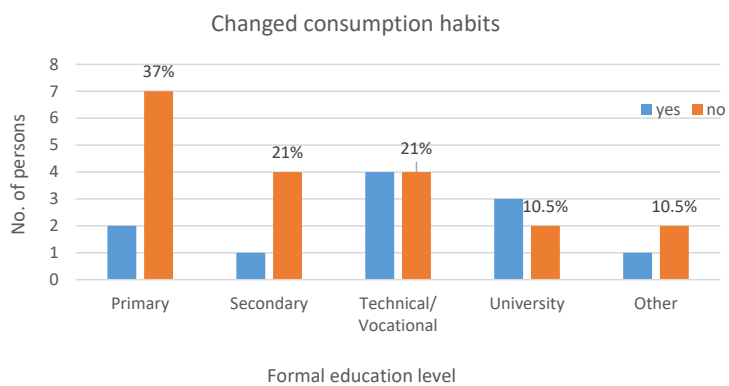

Fig. 4: Changed consumption habits by education level

awareness to the need for management of the limited land resource. It was noticeable however, that Gros Islet town recorded the greatest amount of waste generated, with most respondents indicating that they discarded on average 4-7 bags of trash per house per week. Thus, despite them having taken steps to change consumption patterns to reduce waste generation, they were still high emitters. UNEP (2019) identified the increasing rate of urbanization as a determinant of the need for well managed urban waste SWMS. The residents of Monchy, on the other hand, take no direct action to reduce the amount of waste which they generate. Residents indicated a willingness to effect changes which would help improve SWM in Saint Lucia among which were composting, repurposing waste, segregation/sorting, change in products, recycling, lifestyle changes e.g. less shopping and cooking, reduce consumption, whatever is enforced by the government. This reveals therefore that though they may have not taken major action, they were willing to minimize waste generation. Consequently, the limitations of the current system as it relates to waste generation include the lack of sustainable options for dealing with organics, green waste, and recyclable materials; the existence of a system which favors waste generation, unsustainable SWM practices and environmental pollution; waste generation is coupled with urbanization and population growth; and the failure of SLSWMA to formulate and implement policy and regulations relating to waste reduction, waste diversion and effective material recovery. There are several global initiatives which can be applied to improve the existing system. Ghosh (2016) recognised the need for sustainable SWM in China and India given the rapid population growth and the high volumes of waste generated and thus, proposed that the authority reduce the volume of waste disposed of in landfills e.g. through collection by door-to-door services or in communal containers as well as use of informal waste recyclers which played an important role in recovering recyclables. Various treatment options including incineration, composting, pyrolysis, industrial recycle and reuse, recycle and reuse to achieve the reduction of waste to landfills were identified Ghosh (2016). The German government experienced a shortage of landfill capacity coupled with the need to curb its use of natural resources and energy, so it promoted the "circular economy" which comprises waste separation, treatment and recycling of waste to close substance cycles, thereby favouring sustainability. This it achieved through a programme of public sector measures which outlines existing and potential waste prevention measures at all levels. It focuses on waste prevention strategies and incentives along with advice, information and awareness-raising measures, and research and development projects (BMU, 2018). Japan disseminated a waste reduction policy based on the 3Rs namely reduce, reuse and recycle. The plan emphasized the need for a sustainable lifestyle by urging citizens and businesses to separate their waste at source. This philosophy was instilled in citizens and advocated through a gradual and phased approach. The policy was backed up with environmental education as well as concrete steps including increasingly rigorous separation rules, quality checks and sanctions. These components were further enhanced by the introduction of technological resources such as a mixture of disposal facilities and innovative civil engineering (Jones, 2015). The preceding examples illustrate the importance of environmental education supported by the relevant technologies and socioeconomic framework in addressing SWM issues. Diaz (2017) emphasized the need for rigorous environmental education in developing countries as a solution to the problems of waste management.

Waste storage, collection and transportation

All respondents confirmed that their community benefitted from garbage collection service, which they used and described as good. This service is offered with the help of contracted waste haulers who collect waste curbside where possible, via communal bins or collection points where households could not be accessed by the collection vehicle (SLSWMA, 2016). The service is also "good" because SLSWMA engages contractors and other major stakeholders in sensitization activities (SLSWMA, 2016).Residents attributed adequacy of service to various factors including "frequency of collection" which accounted for 22% of answers, "reliability" i.e. whether garbage was collected on collection days, which accounted for 19%, no charge for collection according to 13% and for 12% it was punctuality of collection (Fig. 5). Nonetheless, the service was not homogenous.

Nine percent of persons indicated that there were other factors which influenced their rating of service provided. Among them was unreliability of

collection evident through the change in collection schedules and irregular collection times/ days; decreased quality of service arising from the more sporadic nature of collection compared with past service; failure to collect bulk waste and green waste; the breakdown of trucks resulting in non-collection of waste; and a need for improvement in the service generally. An illustration of the factors affecting rank by community is presented in Fig. 6.

Monchy was most affected by unreliability in collection i.e. waste was not always collected on scheduled days. Monthly reports from the SLSWMA reflect breakdown of collection vehicles, delays at the landfill and high volumes of waste which exceed the capacity of the trucks for collection as some reasons for non-collection. Gros Islet town and Reduit however, cited frequency of collection as an issue and this may be due to the volume of waste generated, thereby necessitating more frequent collection to clear the waste. The Authority confirmed that these 2 communities generate high volumes of green waste and organic waste and lack the space to store these between collection days (SLSWMA, 2018). Additionally, Gros Islet town is the municipal head for the district and as such, tends to be prioritized in decision-making matters. Reduit is a stable community, whose population comprises primarily older, affluent families who have an organized homeowner's association and consequently are better able to take collective action to address issues within the community. Monchy on the

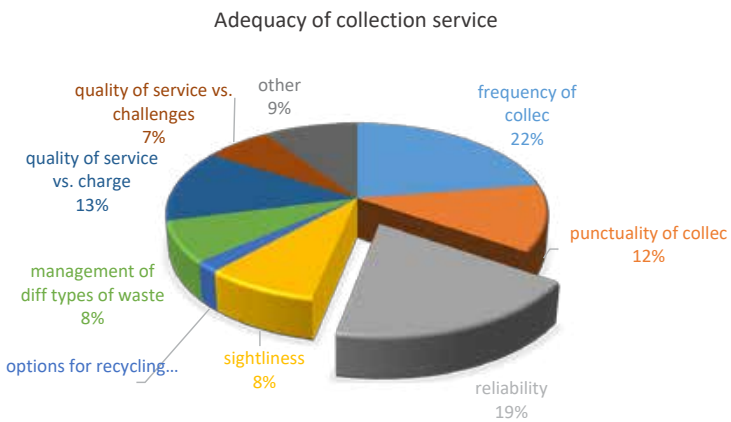

Fig. 5: Factors affecting residents rank of adequacy of garbage collection service

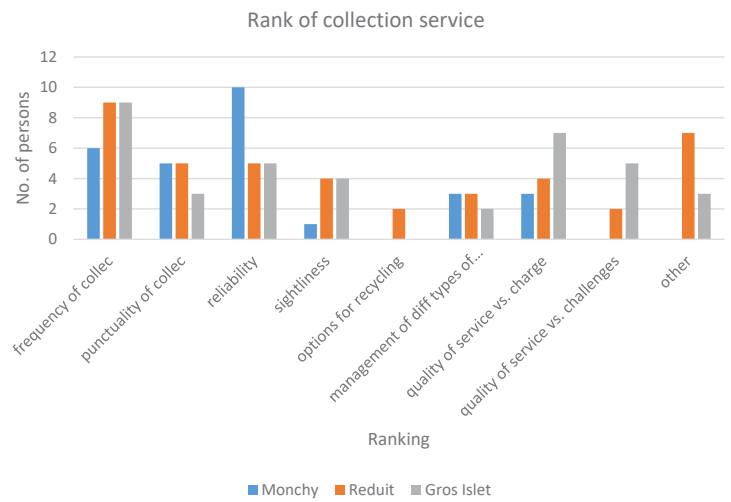

Fig. 6: Factors affecting ranking of service by community

other hand is more rural, less stable and characterized by constantly a changing population. Some participants (40%) indicated that they were willing to pay for improved garbage collection services, although females were less inclined to do so. Respondents from Gros Islet town were more willing to pay while those from Monchy were least willing. Given the foregoing, it was observed that several needs must be addressed to improve collection, storage and transportation in the study area. They were: source sorting of various streams of waste to allow for more efficient collection; provision of compatible infrastructure to enhance collection since the physical environment does not cater for trucks to collect waste at the curb for each household; a proper system and technology for storage and collection to minimize mismanagement between collection days; improved collection technology and system (e.g. the use of proper containers; enhanced education on appropriate practices; introduction of measures which are compatible with the characteristics of each community such as door to door collection, communal bins, incentives and/or sanctions, etc.; and formulation, implementation and enforcement of policies and regulations guiding waste collection for all stakeholders. A possible solution to the problem of waste collection was identified in a public-private-partnership (PPP) between locals and the municipal government in Managua, Nicaragua in which locals formed a cooperative called 'Manos Unidas' and collected waste from areas which are inaccessible by garbage trucks, cleaned the community and collected garbage from residents for a small fee, rather than inappropriate disposal and littering can serve as an applicable practice in the study area. The initiative helped the society respond to several developmental challenges such as poverty reduction, environmental protection, reduction of infant mortality, etc. Members of the communities enjoy a clean, healthy and safe environment while the waste collectors have a stable source of employment. This partnership thus solved two (2) social issues. (MGV Producciones, 2011). Another possible solution was found in the example where Jamaica improved service in 18 communities by means World Bank financing for results-based financing (RBF), waste collection infrastructure investments and community involvement. The initiative called Super 18, involved the provision of trucks, bins, etc. in the most vulnerable areas and generated job creation by introducing environmental wardens from the communities to educate community members, to enforce waste collection and separation practices as well as to hold regular stakeholder meetings in each community as a means to engage members in the project and build trust. Consequently, it contributed to a crime prevention and reduction programme (Burrowes, 2017) and enhanced service delivery (The World Bank, 2019). Thus, authorities must be innovative in addressing SWM challenges.

Waste processing, disposal/treatment

Despite enjoying good collection service, nearly half of respondents indicated that they used other forms of waste disposal. Of those who do, the majority (50%) were from Reduit, followed by Gros Islet town and finally Monchy. There was a noticeable link between education level and use of alternative forms of garbage disposal when many residents with university education indicated that they used alternative methods in addition to the municipal collection service (Fig. 7).

The methods used however, were not dependent on education level i.e. some university graduates engaged in unsustainable methods such as burning while some primary school graduates practiced composting. This indicated that though respondents were cognizant of the need for utilizing alternative methods of waste disposal they may not sufficiently educated on sustainable practices. As it related to the quantity generated and disposed of, Monchy disposed of less waste through the municipal collection service. This can be attributed to the fact cadastral records from the Department of Physical Planning indicated that many households have more yard space to engage in composting, separating and open burning. This contrasts with Gros Islet town where respondents disposed of higher volumes via the municipal services. The residential lots in the community are generally smaller in area, more densely developed with little to no yard space, and neighbors are in closer proximity. Therefore, there is limited space to practice alternative forms of disposal/treatment. Another reason may be that Monchy is less urban, inhabitants can have backyard gardens and produce some of their own food, there are fewer fast-food restaurants and commercial activities, and thus generally generate less waste than the town of Gros Islet which is more urban. The younger respondents indicated that they generally disposed of less garbage (Fig. 8). This may be because they are away

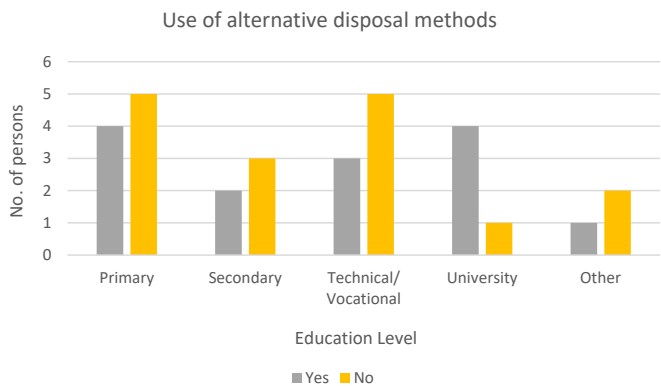

Fig. 7: Use of alternative garbage disposal options by education level

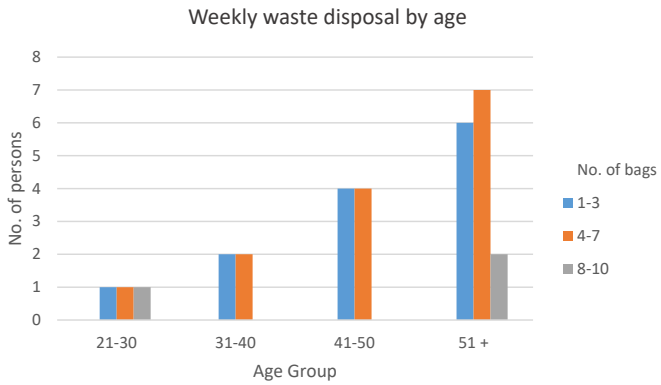

Fig. 8: Quantity of garbage disposed by age

from home more, eat out more, cook less and have different lifestyles than their older counterparts.

Some shortcomings of the current waste disposal system comprise, a non-communitarian attitude to waste disposal among residents whose only concern was individual wellbeing; need for education on environmentally friendly disposal practices; need for a system of monitoring and enforcement including incentives, against illegal and indiscriminate dumping; need for a system (inclusive of policies and regulations) to allow for alternative and sustainable disposal/ treatment methods; existing landfills to be properly maintained; need for resources (for all stakeholders in the sector) to accomplish all the aforementioned initiatives. This is supported by Grigorova *et al.* (2017) who concluded that the increased quantity of the waste products of varied origin has driven the need for revolutionary SWM technologies particularly those focused on treatment and disposal methods. Liikanen *et al.* (2018) studied São Paulo, Brazil to discover alternative treatment alternatives for MSW to reduce the volume of waste to landfills. They found that a progressive, stepped approached which built up on implemented methods was best.

Waste management services

Attitudes towards waste management are important. Females in the study area were less willing to pay to improve waste collection services. Moreover, they believed that their current practices were good and did not need to be changed. Ocean Conservancy (2019) emphasises the cross-cutting role of women in the waste management sector as consumers, recyclers, informal workers, etc. Participants from Gros Islet town were most willing to pay a fee while Monchy residents were least willing. This may be owed to the fact that Gros Islet town suffers the impacts of receiving lots of visitors who further exacerbate problems of the high volumes of waste generated, and consequently, needing disposal. Monchy on the other hand does not

receive visitors as frequently, and, given the land space residents practice alternate forms of waste disposal. As such, waste collection and disposal /treatment are less problematic for them. This factor (payment to improve service) was considered in the context that residents do not currently pay a fee and consequently may feel that the government is obligated to provide this free service. An alarming factor is that residents continue to engage in illegal dumping and indiscriminate littering despite the free service offered. It raised concerns of what their reaction will be if fees are imposed for collection service. Overall residents of Monchy showed more willingness to change their current waste management practices, and Reduit showed less. The reasons indicated were similar and included concern for the environment (25%), concern for family well-being (22%) and benefits to them (24%). Other reasons presented were, their current practices were adequate, and wished to contribute to the common good of the community (Fig. 9).

Fear of fines and sanctions was seldom identified as a reason for changing disposal practices. This may be reflective of poor enforcement of existing regulations or a lack of enabling legislation which results in residents having little to no concern about punitive actions. Policy, legislation and government priority also play a major role in the sustainability of WMS (Henry *et al.* 2017). Residents of the study area were willing to try alternative methods of SWM but were concerned about the inconvenience of the new methods. This revealed that any proposal must consider awareness building and culture change so that residents understand how lifestyle change could improve their circumstances and not necessarily be a negative thing. It also highlighted the need for public participation and involvement in decision making to ensure success (Chang and Pires, 2015). The SLSWMA engages in continuous public awareness activities to educate residents. However, this has not resulted in the requisite attitudinal change on a wide scale. This indicated that education alone is inadequate. This strengthens the need for supporting policy as supported by Guerrero *et al*. (2013) who state that adequate legislation is needed to ensure the effectiveness of solid waste management policy. Germany's successful recycling programme is attributed to appropriate policy coupled with the establishment of necessary systems of monitoring and enforcement (Nelles, *et al.,* 2016). Respondents indicated willingness to make changes to improve waste management in their community (Fig. 10) and some remarked that they were already taking alternative action such as carry waste to recycling depot and cleaning their environs. Others stated that they would do whatever is enforced (by government) while yet other commented that they like the convenience of current practices and that whatever options are offered should not be too time consuming.

SLSWMA has power to elaborate policy and regulations to institutionalize SWM based on reduction, reuse, recycling, recovery and separation, however, it had not done so at the time of the study. Brassaw (2017) indicated that Germany's Waste

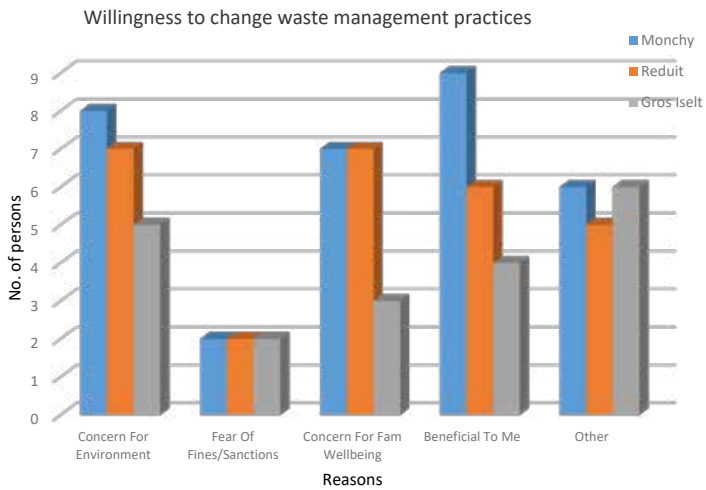

Fig. 9: Reasons impacting willingness to change waste management practices

Fig. 10: Changes respondent willing to make for improved waste management in Saint Lucia

Management and Renewable Energy Programs are very successful because of strong government policy and citizens embracing recycling. Notwithstanding the lack of legislative instruments, SLSWMA continued its attempts to operate the disposal facilities according to international standards, attempting to apply best practices to prevent harm to human and environmental health (SLSWMA, 2016). It is however severely limited by a lack of resources, inadequate legislation/policy, and challenges in the environment, which is common to waste managers in developing countries. The current waste management services therefore suffers deficiencies such as the lack of waste management approaches appropriate for all age, gender and socioeconomic groups; lack of an education plan which promotes the positives of waste management such as economic and environmental benefits; lack of initiatives/approaches which adequately balance proper waste management with the residents' convenience; lack of a comprehensive management system and strategy which clearly identifies roles, responsibilities, resources, monitoring and enforcement activities, etc.; lack of capacity of the SLSWMA to effectively and efficiently implement and govern the current SWM system, and possibly the newly proposed one. Moreover, SLSWMA alone cannot address the existing deficiencies in the system. Willmott and Graci (2012) acknowledged the importance of collaborative approaches to management and decision-making, to address problems too complex to be effectively resolved by independent action. Their research focused on providing an answer to governance and management issues as a means of improving operations, waste related behaviour, education and awareness matters, knowledge and network sharing and overall increased institutional capacity.

CONCLUSION

Solid waste management is a global issue which affects all countries and so, must be urgently addressed since the impacts are wide-ranging and far-reaching. Many countries are seeking practical solutions, especially SIDS whose peculiar mix of physical and socioeconomic characteristics exacerbate their challenges. Although this research aimed to present a SWM system which could become a model for other SIDS, it was noted that SWM is a very dynamic activity and is influenced by multiple variables which differ for each territory. Consequently, each territory requires a system which is unique to its mix of characteristics. In the case of the study area the main requirements were resources (physical, technical, human and economic), environmental education and institutional strengthening. This was derived from assessment of the existing system as it relates to the socioeconomic and cultural framework, legislative and policy framework, institutional framework, and the environmental characteristics. Many of the deficiencies of the SLSWMA could be addressed by investing the requisite financial resources or implementing innovative measures such as sharing management activities with community organizations or establishing PPPs. The resultant framework would then have to be supported by widespread environmental education for all stakeholders, as well as the appropriate legislative and policy framework to result in changed behaviours. The researchers realized that the existing deficiencies in the SWMS in the study area are mammoth in scope and cannot all be addressed at once. Consequently, it identified the top actions which could be immediately implemented in order to address the SWM problem in the short to medium term. These are, the conduct of a legislative review inclusive of the requisite policies, regulations and amended legislation to establish an adequate legislative framework for effective SWM. Next would be the preparation of a comprehensive Solid Waste

Management Strategy since this will underpin many of the other actions needed. Thirdly, there would be need for widespread public environmental education and sensitization on the proposed solid waste management system, the role of the various actors, benefits to be derived, goals to be achieved and the actions to be implemented. An important activity would be the implementation of actions to change the perception of residents of the Waste Management Sector and associated professions such as waste haulers, pickers and material recovery crews, to make them more attractive and socially acceptable, while highlighting their importance. Finally, would be the creation of a sense of pride, belonging, stewardship and shared responsibility among residents, to their communities and environment. This study concluded that it is the responsibility of each society to assess its existing context and propose a system which will address its exclusive situation. Consequently, there is no existing SWMS which can be taken and applied directly to any other territory, however, certain components or practices can be borrowed, modified and applied to the unique context of the intended area.

AUTHOR CONTRIBUTIONS

J. Weekes is the main author who conducted on-site research, collated and interpreted data, analysed findings and prepared the manuscript. J.C. Musa, K. Malavé and C. Morales helped in the literature review, editing and data analysis.

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CONFLICT OF INTEREST

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

ABBREVIATIONS

BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
collec	Collection
CSOSL	Central Statistics Office of Saint Lucia
diff	Different
e.g.	For example
etc.	Etcetera
i.e.	That is
IRB	Institutional Review Board
Fig.	Figure
Kg.	Kilograms
MGV Producciones	María Gabriela Vega Producciones
MSW	Municipal solid waste
No.	Number
PPP	Public private partnerships
RBF	Results-based financing
SIDS	Small island developing states
SLSWMA	Saint Lucia Solid Waste Management Authority
SWM	Solid waste management
UNEP	United Nations Environment Programme
vs.	Versus
%	Percent

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ORIGINAL RESEARCH PAPER

Residual organochlorine pesticide contaminants profile in fish and sediment from a dam

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ABSTRACT

BACKGROUND AND OBJECTIVES: The vulnerability of the Sankana dam to organochlorine pesticide contamination is a major cause for concern. Indigenes rely on the dam for drinking water and irrigation of their farmlands as well as for fish and other aquatic delicacies. Virtually there exists no study on the residual levels of organochlorine or other pesticide contaminants in the dam despite its susceptibility to pesticide contamination. In the present study, the levels of organochlorine residues in fish and sediments from the Sankana dam were assessed.
METHODS: Pesticide residue extraction was achieved using acetonitrile containing 1% (v/v) acetic acid in the presence of sodium acetate, sodium citrate and magnesium sulphate followed by purification over activated florisil and sodium sulphate. Identification and quantification of residue extracts was done using a gas chromatograph conjugated with mass spectrometer.
FINDINGS: In all, varying levels of 13 organochlorine residues were detected, 11 of which were found in fish and 12 in sediment. Average mean levels of organochlorine residues found in fish ranged from 0.001 - 0.277 mg/kg. Residual levels of beta-hexachlorocyclohexane, delta-hexachlorocyclohexane, gamma-hexachlorocyclohexane, endosulfan-A and dichlorodiphenyldichloroethane in fish were relatively higher than their respective levels in sediment. Organochlorine residues found in sediment also ranged from 0.001 - 0.091 mg/kg. Dichlorodiphenyldichloroethylene, aldrin, dieldrin, endrin, methoxychlor, heptachlor, gamma-chlordane and endosulfan-B residual levels in sediment were higher than the corresponding levels in fish.
CONCLUSION: The study provides a baseline for continuous/regular monitoring of organochlorine contaminants in the Sankana dam and other waterbodies upstream and downstream. Where organochlorine residues exceeded their recommended permissible thresholds typically suggests possible recent/continuous use of such pesticides within the catchment area. There is therefore the need for appropriate measures and/or need to strengthen existing policies that bans the importation, sale and use of organochlorine pesticides via strict enforcement.

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INTRODUCTION

The world over, agriculture remains a major economic growth determinant contributing significantly to Gross Domestic Product (GDP) growth rate (Johnston, 1970; Enu, 2014). Citing Ghana as a case study, there exists a direct correlation between agricultural and GDP growth rates (Enu, 2014). According to the World Bank Group Economic Update, over 20% of Ghana's GDP is attributable to agriculture and is the major source of raw materials for Ghana's industry- supporting nearly 67% of non-oil manufacturing. Agriculture is a major employer of nearly half of Ghana's labour force and a principal livelihood source for the majority of individuals mostly found in the remote parts of Ghana (World Bank Group, 2018). Agriculture in Ghana and many low and middle-income countries extensively rely on the use of chemical or biological agents or their mixtures-collectively called pesticides to control insects and pests known to pose threat to crop yield and quality (Kaur *et al.,* 2019). Thus, pesticide usage has become an integral part of present-day agriculture worldwide. The world has in the past few decades witnessed a surge in the use of various types of pesticides in huge quantities. As captured by Kaur *et al.* (2019), on the average, an estimated 5.2 billion pounds of pesticides are used annually across the globe. Aside the critical role pesticides play in agriculture, they constitute a major class of toxic environmental contaminants worthy of concern as they pose a threat to non-target organisms such as humans and other living organisms (Yadav and Devi, 2017; Jeyakumar *et al.,* 2014). Quite a number of pesticides and their metabolites have been cited to adversely impact the environment and cause reproduction and birth defects in humans (Edwards, 1993), as well as immune system impairment, cancer and disruptions in the endocrine system (WWF, 1999). The estimated death toll worldwide due to pesticide toxicity is between 5000 - 20000 out of an estimated total of 500000 - 1000000 people who get exposed annually (Yadav *et al.,* 2015; FAO/WHO, 2007). Close to 50% of those poisoned and 75% of those that die are agricultural sector workers (Yadav and Devi, 2017). One class of pesticides that have seen extensive usage on the global front are organochlorine pesticides (OCPs) (Darko *et al.,* 2008). In Ghana, OCPs have been used for over 4 decades (Ntow, 2001) and perhaps counting. Despite being banned some 25 years ago (Darko *et al.,* 2008), OCPs till date remain the preferred choice of most Ghanaian farmers owing to their relatively low cost and effectiveness against a wide range of pests (Ntow *et al.,* 2006; Racke *et al.,* 1997; Sivakumar, 2015). Notwithstanding the fact that the use of OCPs is prohibited in Ghana, they nonetheless find their way onto most Ghanaian farms (Ntow *et al.,* 2006; Akoto *et al.,* 2016) particularly in the hinterlands suggestive of the illegal production, usage and trading in these chemicals (Darko and Acquaah, 2007). The health threats posed by pesticide residues to humans and other life forms within the environment have ignited research interests into the subject matter the world over. In Ghana and Africa at large, several studies into the subject matter have confirmed several pesticide residue contaminants to be present in water bodies, sediments, fish and other aquatic organisms as well as food crops (Darko *et al.,* 2008; Ntow *et al.,* 2006; Akoto *et al.,* 2016; Fosu-Mensah *et al.,* 2016; Abagale *et al.,* 2014; Essumang *et al.,* 2009). For instance, the health risks posed by the consumption of fish from the Tono Reservoir in the Kassena-Nankana District of the Upper East Region of Ghana was evaluated by Akoto *et al.* (2016) having assessed the residual levels of organochlorine (OC) and organophosphorus (OP) pesticides in fish, sediment and water samples from the reservoir. Health risk assessment revealed aldrin to have the potential to cause toxicity to systems in persons consuming fish from the reservoir. Elsewhere in the Tolon District of Ghana, Abagale *et al.* (2014) also studied OCP levels in irrigation water from the Golinga Dam. Recorded OCP residue levels here were all above the WHO maximum residue limit (MRL) for drinking water except mirex posing a serious health hazard to humans, aquatic life as well as the irrigated crops. Fosu-Mensah *et al.* (2016) in a related study assessed OCP residue levels in soils and drinking water sources in selected cocoa growing areas in Ghana and detected residues of seven banned OCPs in the various matrices analysed, suggestive of the illegal use and trading in such pesticides. Prevalent in Ghana are crop farms that are often sited along the banks of waterbodies (streams, lakes, rivers, dams) for easy access to water for irrigation. The practice essentially has exposed most of such waterbodies to pesticide contamination through run-offs from these farms (Bocquene and Franco, 2005). Such is the case in Sankana, a small community within Nadowli-Kaleo District of the Upper West Region of Ghana

noted for producing the bulk of crops such as cereals and grains and vegetables in the District. Pivotal to the sustenance of crop farming here is the Sankana dam which is one of 84 dams within the Upper West Region (Kpieta *et al.,* 2013). The dam typically serves as a primary water source for irrigation and drinking particularly during the dry season (Kpieta *et al.,* 2013; Kpieta and Laari, 2014; Namara *et. al.,* 2011). As may be the case elsewhere, the control of pest infestation by farmers here is largely by the use of pesticides, predominantly OCPs. Pesticide application within this catchment can be described as haphazard. Coupled with this is the unscrupulous disposal of pesticide wastes or their containers and washouts on farmlands. Thus, the Sankana dam as well as other water bodies upstream and downstream of these farmlands are prone to pesticide contamination from drifts during spraying, run-offs from farmlands when it rains and the disposal of pesticide wastes, their containers or washouts into these water bodies (Akoto *et al.,* 2016). The threat posed by OCPs to humans and other life forms is heightened by their persistent attributes and resistance to physical, chemical and biological degradation as well as their ability to bio-accumulate along the food chain owing to their lipophilicity and their tendency to be transported over long distances (Fosu-Mensah *et al.,* 2016; Chau, 2005; Pandit *et al.,* 2006; Guo *et al.,* 2008). The vulnerability of the Sankana dam to OCP contamination is a major cause for concern worth the necessary attention as indigenes aside relying on the dam for irrigation of their farmlands also rely on it for fish and other aquatic organisms and as a source of drinking water for both humans and livestock. Virtually, no study has been conducted to assess the levels of OCP or other pesticide residues in the Sankana dam despite the potential contamination of this dam with pesticide residues. The present study on this account was conducted to assess the levels of OCPs in fish and sediments obtained from the Sankana dam to establish a baseline for continuous monitoring of such contaminants in the Sankana dam and other waterbodies upstream and downstream. The study was conducted at Sankana in the Nadowli-Kaleo District of the Upper West Region of Ghana in 2020.

MATERIALS AND METHODS

Study location

Sankana is a village within Nadowli-Kaleo District of the Upper West Region of Ghana. Sankana is 26.3 km away from the administrative capital, WA. Located within this village is the Sankana dam built in 1972 (Kpieta *et al.,* 2013) which happens to be the largest of 4 dams in Sankana and the district at large (Peprah *et al.,* 2015). Sankana is located at 10° 12′ 0″ North, 2° 35′ 0″ West, surrounded by beautiful scenery of igneous rocks. Sankana is boarded by communities including Nadowli, Changu, Kaluri, Nyembale, Gyile, Papu, Perintabo and Gbanko, all within the Nadowli-Kaleo District of the Upper West Region of Ghana. Generally, the landscape has a smoothly rising and falling pattern, rising between 150 m to 300 m with spot heights of 600 m (Peprah *et al.,* 2015). Sankana falls within the Guinea Savanna Ecological Zone with one rainy season which lasts for six months beginning in May and ending in October with 1000 - 1150 mm of rainfall annually. The highest and lowest temperatures of 36°C and 27°C respectively occur in March and August with relative humidity during the rainy season being 70-90% and 20% during the dry season. The climate here is well suited for tussock grass and fire-resistant deciduous trees such as kapok, shea, baobab, mango, dawadawa, cashew, black berries, red berries, teak, acacia and neem (Peprah *et al.,* 2015; Dickson and Benneh, 1988). Fig. 1 depicts the relative location of the study area within the Upper West Region.

Glassware cleaning

Glasswares used were thoroughly washed with warm water and detergent and rinsed with distilled water. Glasswares were further rinsed with acetone and oven dried for 2 hours at 180°C (Darko *et al.,* 2008; Therdteppitak and Yammeng, 2003).

Sample collection

Sampling was done on a monthly basis over a period of 3 months beginning January to March, 2020. Random sampling was employed. Fish samples (FS) and sediment samples (SS) were obtained from each of three zones namely- upstream (U), midstream (M) and downstream (D) of the Sankana dam. A total of 45 FS and 90 SS comprising 15 FS and 30 SS per sampling zone were worked on. FS were purchased directly from fishermen at each sampling zone. Fish composite samples for each sampling zone comprised 5 different fish species. FS were wrapped in pre-cleaned aluminium foil (Ntow, 2001), placed in an ice thermo insulator box and transported to the

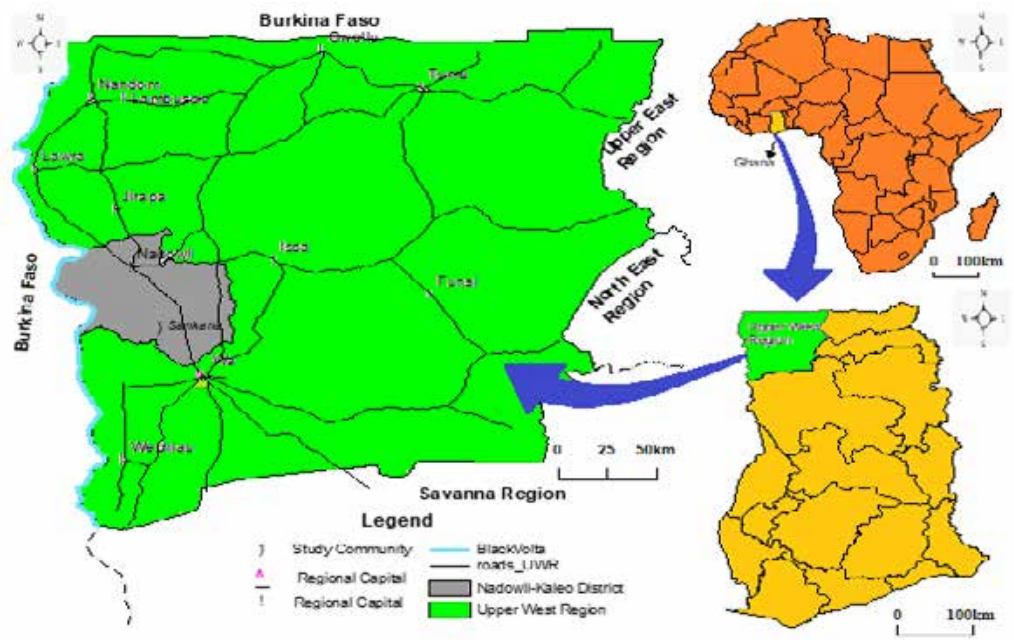

Fig. 1: Geographic location of Sankana in the Upper West Region of Ghana

laboratory (Darko *et al.,* 2008; Essumang *et al.,* 2009). SS were collected with the help of the fisherfolks at each of the sampling zones. At each sampling zone, SS were randomly collected from 10 different locations using a soil scoop and homogenized into a composite sample (Ntow, 2001; Fosu-Mensah *et al.,* 2016). Samples were transferred into 100 mL wide-mouthed glass bottles, capped, labelled and transported to the laboratory in an ice thermo insulator box (Darko *et al.,* 2008).

Sample preparation

In the laboratory the FS were rinsed severally with ion-free water. The intestines and scales of FS were removed and the muscle tissues cut into shreds and freeze dried for 72 hours. After freeze drying, the chopped muscle tissue samples were blended together using a waring blender (stainless) to form a homogenized powdered sample. The powdered fish sample was stored at 4°C in a fridge awaiting extraction (Darko *et al.,* 2008; Therdteppitak and Yammeng, 2003; Essumang *et al.,* 2009). Composite SS were poured out of their containers onto pre-cleaned aluminium foils and allowed to air dry for 72 hours followed by oven drying at 105°C for 24 hours. SS were then grinded with pestle and mortar, sieved using 250 µm mesh size sieve (Ntow, 2001;Fosu-Mensah *et al.,* 2016).

Residue extraction

Pesticide residue extraction from powdered fish and grinded sediment followed the method used by Kolberg *et al.* (2010) with little modification. 100 mL of deionised distilled water was added to 200 g of powdered fish and grinded sediment in each instance and the mixture homogenized at high speed using an Ultraturrax blender to obtain a homogeneous slurry/paste. A 10 g portion of fish paste and sediment paste were weighed into individual 50 mL centrifuge tubes. 10 mL of acetonitrile (C_2H_3N), containing 1% (v/v) of acetic acid (CH_3COOH) was added to the content of each tube and each mixture hand shaken for 1 min. 3 g of magnesium sulphate ($MgSO_4$) was added to each mixture and immediately hand shaken for another minute. 1.7 g of sodium acetate ($C_2H_3NaO_2$) and 1 g of sodium citrate ($Na_3C_6H_5O_7$) were added sequentially to the content of each tube and the resulting mixture in each case vigorously hand shaken for another minute. The tubes with their content were finally centrifuged at 4000 rpm for 8 mins. The resulting supernatant in each instance was carefully transferred into a suitable container for subsequent clean up.

Purification of residue extracts

Prior to chemical analysis, the residue extracts were purified to rid them of interfering materials or compounds that may have been extracted along with the pesticide residues. Into a micro column plugged with glass wool was added 1.5 g of activated florisil (MgO_3Si) followed by the addition of 1.5 g sodium sulphate (Na_2SO_4). The clean-up was preceded with conditioning of the micro column with 10 mL ethyl acetate. The residue extract was transferred onto the column and allowed to elute. Using the Buchi RE-200 rotary vacuum evaporator, the eluted sample in each instance was evaporated to dryness. The resulting residue afterwards was dissolved in 2 mL of ethyl acetate. The dissolution step was repeated two more times and all samples pooled together. Using a glass pipette, a sample of the purified residue extract was transferred into a 1.5 mL vial for subsequent chemical analysis (Baah, 2016).

Analysis of residue extracts

Pesticide residue analysis was carried out at the Organic, Instrumental and Physical Research Laboratory of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ashanti Region, Ghana. Chemical analysis of residue extracts was done using a gas chromatography (GC) coupled with a mass spectrometer (MS).

Standardization

A certified pesticide standard mix (*Pesticide Mix 13, 10 µg/mL in Toluene*) containing 31 analytes was purchased from Ehrenstorfer, GmbH, Germany in a sealed vial for use. To 10 g of blank working samples were added 10 µL, 30 µL, 50 µL, 150 µL and 300 µL of the standard stock solution in each instance to obtain spiked calibration curves at 5 levels of 10, 30, 50, 150 and 300 ng/g. Standardization solutions for the calibration were prepared in triplicates. 10 µL of a stock solution of triphenylmethane (TPM) in acetonitrile at a concentration of 1 mg/mL was added to the spiked samples as internal standard. Spiked samples were subjected to same treatment as the working samples (Nasiri *et al.,* 2016).

Residue analysis by GC-MS

The Agilent Technologies 6890 Network GC System with single quadruple detector equipped with an Agilent 7683B autosampler was employed for the analysis of residue extracts. Chromatographic separation was achieved using an HP-5 capillary column with dimensions-30 m × 0.25 mm internal diameter and 1 µm film thickness. Helium gas at 99.999% purity was applied as carrier gas at 1 mL/min steady flow rate. Oven temperature was 75°C initially, held for 3 mins and increased at 25°C/min ramp rate to 120°C and finally to 300°C at 5°C/min ramp rate. The final temperature of 300°C was held for 11 mins. The injector temperature was kept at 250°C. 1 mL aliquots of extracts were injected into the GC. The GC and MS were respectively operated in the splitless and electron ionization (70 eV) modes. The split valve was kept closed for 0.75 min. GC-MS interface, ion source and quadruple temperatures were respectively 266, 230 and 150°C. The MS was operated in the time-scheduled selective ion monitoring (SIM) mode for the quantitative determination OCs (Nasiri *et al.,* 2016; Jahanmard *et al.,* 2016).

Identification and quantification

A sample of the pesticide standard mix of known concentration was run through the GC-MS setup under same conditions to ascertain the retention times and peak areas of the individual compounds/analytes in the standard matrix prior to analysis of the extracts. Identification and quantification of compounds/analytes in working samples (extracts) was achieved via comparison of the retention times and peak areas of compounds detected in the working sample (extracts) with that found in the standard. All analyses were conducted in triplicates (Baah, 2016).

Analysis of data

One-way analysis of variance (ANOVA) was performed to establish whether the differences in the means of experimental data for the various OC compounds/residues found across the different sampling zones were significant or otherwise. The degree of correlation between OC residual levels in fish and sediment for each sampling location was also evaluated. Statistical analyses were performed using Minitab statistical software (17) and Microsoft Excel (2016). Tests with $p < 0.05$ were deemed significant statistically.

RESULTS AND DISCUSSION

The quest to improve agriculture or crop yield and reduce losses caused by pests and insects has triggered a surge in the use of pesticides worldwide.

The present study sought to establish baseline levels of OC residues in the Sankana dam in the Nadowli-Kaleo District of the Upper West Region of Ghana. The present study revealed varying levels of 13 different OC compounds in fish and sediment (combined) obtained from the Sankana dam. Conveyed in Table 1 and Table 2 are the mean concentrations of OC compounds found in fish and sediment across the various sampling zones with Fig. 2 showing total OC residual levels across sampling zones. Table 3 compares the average mean levels of OC residues found in fish and sediment with their respective maximum residue limits (MRLs).

OC levels identified in fish and sediment across sampling zones

Varying levels of OC residues were detected in fish and sediment across the different sampling zones in the present study. Fish obtained upstream, midstream and downstream of the Sankana dam in all contained 11 OC residues including aldrin, endrin, endosulfan-A, heptachlor, methoxychlor, beta hexachlorocyclohexane (β-HCH), gamma-hexachlorocyclohexane (γ-HCH), delta hexachlorocyclohexane (δ-HCH), gamma (γ)-chlordane, dichlorodiphenyldichloroethylene (*p,p'*-DDE) and dichlorodiphenyldichloroethane (*p,p'*-

Table 1: Mean concentrations of OC residues in fish across sampling zones

OC Residues/ Compounds	Mean Concentration (mg/kg ± SD)		
	Fish		
	FS_U	FS_M	FS_D
Aldrin	0.019±0.00	0.004±0.00	0.008±0.00
β-HCH	0.663±0.01	ND	0.167±0.01
γ-HCH	0.014±0.00	ND	0.080±0.01
δ-HCH	0.077±0.02	0.009±0.00	0.045±0.01
Dieldrin	ND	ND	ND
Endrin	ND	0.003±0.00	0.002±0.00
Endosulfan-A	0.043±0.00	0.011±0.00	0.045±0.00
Endosulfan-B	ND	ND	ND
Heptachlor	0.027±0.00	0.027±0.01	ND
p,p'-DDE	ND	ND	0.026±0.01
p,p'-DDD	ND	ND	0.003±0.00
Methoxychlor	0.049±0.01	ND	0.021±0.00
γ-Chlordane	0.016±0.00	0.006±0.00	ND

Table 2: Mean concentrations of OC residues in sediment across sampling zones

OC Residues/ Compounds	Mean Concentration (mg/kg ± SD)		
	Sediment		
	SS_U	SS_M	SS_D
Aldrin	ND	ND	0.093±0.01
β-HCH	0.111±0.01	0.135±0.01	0.028±0.00
γ-HCH	0.029±0.00	ND	ND
δ-HCH	0.023±0.00	0.007±0.00	ND
Dieldrin	ND	ND	0.069±0.01
Endrin	0.004±0.00	0.003±0.00	0.002±0.00
Endosulfan-A	0.007±0.00	0.006±0.00	0.011±0.00
Endosulfan-B	ND	ND	0.003±0.00
Heptachlor	ND	ND	0.097±0.01
p,p'-DDE	ND	ND	0.156±0.01
p,p'-DDD	ND	ND	ND
Methoxychlor	ND	ND	0.103±0.01
γ-Chlordane	0.020±0.00	0.016±0.00	ND

*SD = Standard deviation
*ND = None detected

Table 3: Average mean OC residual levels in fish and sediment in relation to their MRLs

OC residues/ compounds	Average mean concentration (mg/kg)		MRLs (mg/kg)
	Fish	Sediment	
Aldrin	0.010	0.031	0.01
β-HCH	0.277	0.091	0.01
γ-HCH	0.031	0.010	0.01
δ-HCH	0.044	0.010	0.01
Dieldrin	ND	0.023	0.05
Endrin	0.002	0.003	0.01
Endosulfan-A	0.032	0.008	0.05
Endosulfan-B	ND	0.001	0.05
Heptachlor	0.009	0.032	0.01
p,p'-DDE	0.009	0.052	0.05
p,p'-DDD	0.001	ND	0.05
Methoxychlor	0.023	0.034	0.01
γ-Chlordane	0.007	0.012	0.01

DDD). Similarly, sediments obtained upstream, midstream and downstream in all also revealed the presence of 12 OC residues including the first 10 OC residues mentioned above in addition to dieldrin and endosulfan-B. Found absent in fish across the different sampling zones were dieldrin and endosulfan-B (Table 1) with *p,p'*-DDD being the only OC residue found absent in sediment across the different sampling zones (Table 2).

OC pesticide residue levels recorded in fish ranged from 0.002±0.00 - 0.663±0.01 mg/kg and from 0.002±0.00-0.156±0.01mg/kg in the case of sediment. The upper limits in each instance exceeded the MRL of 0.05 mg/kg. The highest concentration of 0.663±0.01 mg/kg was recorded for β-HCH in FS_U while the least concentration of 0.002±0.00 mg/kg was recorded for endrin in FS_D (Table 1). *p,p'*-DDE emerged the OC residue in sediment that recorded the highest concentration of 0.156±0.01 mg/kg with endrin recording the least concentration of 0.002±0.00 mg/kg. The highest and least OC concentrations here were both recorded in SS_D (Table 2). Generally speaking, mean OC residual levels recorded in FS_U and FS_M were relatively higher than the levels found in their respective SS ($FS_U > SS_U$ and $FS_M > SS_M$). On the contrary, OC residual levels in SS_D were in general relatively higher than the corresponding levels in FS_D ($SS_D > FS_D$) (Table 1; Table 2). OC compounds characteristically accumulate more in aquatic organisms and settle considerably on sediments owing to their low solubility in water (Akan *et al.,* 2014). Per their lipophilic-hydrophobic nature, OC compounds have the propensity to bio-accumulate in the fatty tissues of fish (Akoto *et al.,* 2016) and to be retained within the organic phase of sediments (Adeyemi *et al.,* 2008). In general, higher mean levels of OC residues recorded in fish in the several instances in the present study could be ascribed to the feeding habits of the different fish species across the sampling zones. According to Muralidharan *et al.* (2009), the degree/rate of OC accumulation in fishes is largely influenced by their feeding habits. In the case of sediment, studies have it that, smaller particles with large surface area as well as those with high organic content show highest adsorption/retention capacities (Elder and Weber, 1980). The level/degree of OC adsorption and retention here would thus be dependent on the surface area and organic matter content of sediments. That is to say, the relatively higher mean levels of OC residues recorded for sediment in the few instances in the present study were not far from expectation. The above observations were thus largely influenced by the different fish species and their feeding habits across the sampling zones and the possible variations in adsorptive capacities of upstream, midstream and downstream sediments. Prevalence of OC contaminants in relation to the number of OC residues identified at the various sampling zones followed the pattern $FS_D > FS_U > FS_M$ and $SS_D > SS_U > SS_M$ respectively for fish and sediment suggestive of a direct correlation between fish and sediment per sampling zone (Table 1; Table 2). Estimated total OC residual levels were highest in FS_U and least in FS_M. In respect of sediment, total OC residual levels contrarily were highest in SS_D and least in SS_M

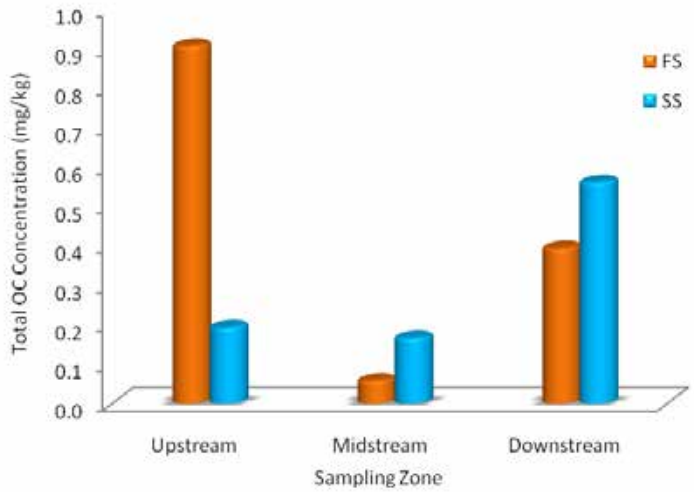

Fig. 2: Total OC residual levels in fish and sediment acroos sampling zones

(Fig. 2). These observations could be explained in relation to the prevalent farming activities upstream and downstream of the Sankana dam.

Total OC residual levels in fish across the different sampling zones were not statistically different ($p > 0.05$) per one-way ANOVA analysis conducted. Total OC residual levels in sediment across the different sampling zones were similarly not statistically different ($p > 0.05$). Tukey simultaneous tests for differences of means between the pairs FS_M-FS_U, FSD-FS_U, FSD-FS_M in the case of fish and SS_M-SS_U, SSD-SS_U, SSD-SS_M in the case of sediment were statistically insignificant ($p > 0.05$). One-way ANOVA analysis comparing mean OC levels in fish and sediment from same sampling zone showed no statistical differences ($p > 0.05$) in each instance. Correlation analysis revealed a strong positive correlation ($r^2 = 0.904$) between OC residual levels in fish and sediment obtained upstream (Fig. 3) with OC residual levels in fish and sediment obtained midstream and downstream showing very weak positive correlations ($r^2 = 0.023$ and $r^2 = 0.026$ respectively) (Fig. 4 and Fig. 5). OC residual levels in essence were prevalent upstream relative to the levels midstream and downstream of the dam. Individuals are thus more prone to OC residue exposure from the consumption of fish particularly obtained upstream.

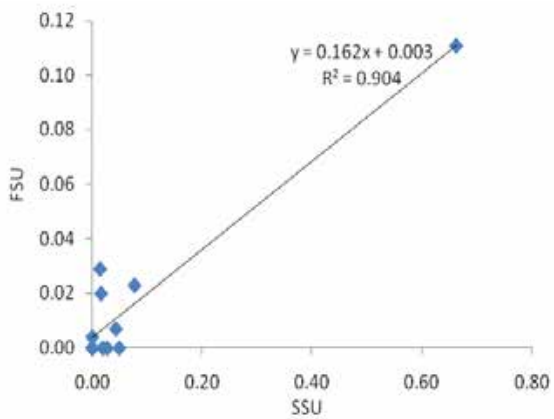

Fig. 3: Correlation between OC levelsin FS_U and SS_U

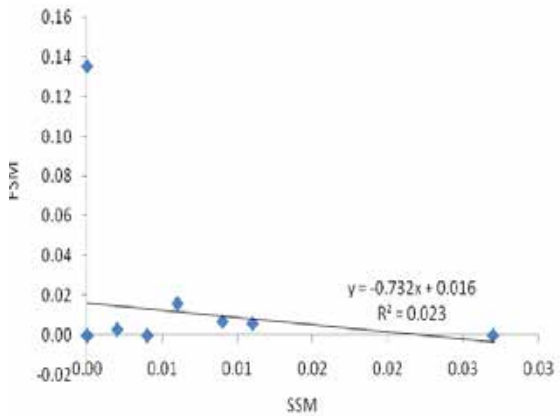

Fig. 4: Correlation between OC levels in FS_M and SS_M

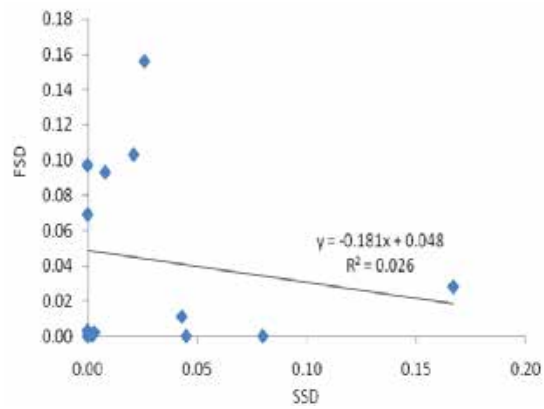

Fig. 5: Correlation between OC levels in FS_D and SS_D

β-HCH, γ-HCH and δ-HCH

β-HCH and δ-HCH were respectively absent in FS_M and SS_D with γ-HCH also being absent in FS_M as well as SS_M and SS_D. Thus β-HCH, γ-HCH and δ-HCH were in general prevalent in upstream and downstream fish as well as in upstream and midstream sediment (Tables 1; Table 2). The average mean levels of β-HCH, δ-HCH and γ-HCH in fish across the dam (in entirety) were respectively 0.277 mg/kg, 0.044 mg/kg and 0.031 mg/kg reflecting a prevalence pattern of β-HCH > δ-HCH >γ-HCH in fish. β-HCH and γ-HCH average mean levels in fish were about 3-times the average mean levels found in sediment (0.091 mg/kg, 0.01 mg/kg). In the case of δ-HCH, average mean level in fish was 4.4-times the average mean level in sediment (0.01 mg/kg) (Table 3). In contrast to the study by Akoto *et al.* (2016), that recorded no β-HCH, γ-HCH and δ-HCH residues, the present study found considerable levels of these compounds. β-HCH is well known to adsorb strongly to organic matter in soil and as such difficult to be lost through evaporation once adsorbed to soil compared to the other isomers. *γ*-HCH and other isomers of hexachlorocyclohexane (HCH) have been revealed in studies to be readily transformed within the environment into β-HCH (Unyimadu *et. al.,* 2018). The relatively higher β-HCH levels than γ-HCH and δ-HCH recorded in both fish and sediment in the current study could thus be ascribed to the above reasons (Table 3) and may not necessarily be suggestive of continuous use of these pesticides within the study area for the control of pests and insects. Comparatively, the average mean levels of these compounds in fish exceeded their MRL of 0.01 mg/kg. In the case of sediment, the average mean levels of these compounds were greater or equal to their MRL of 0.01 mg/kg.

Aldrin, dieldrin and endrin

Aldrin residues were present in all fish and sediment samples except SS_U and SS_M. Dieldrin however was only found in SS_D with endrin being absent in only FS_U (Table 1; Table 2). Average mean level of aldrin in fish and sediment were higher than the average mean levels of dieldrin and endrin in fish and sediment. The average mean levels of these OC compounds in sediment were higher than in fish. Average mean level of aldrin in sediment (0.031 mg/kg) was about 3-fold the aldrin level (0.01 mg/kg) in fish. For dieldrin, the average mean level in sediment was 0.023 mg/kg with the corresponding level in fish well below detection limit (< 0.001). Average mean level of endrin in sediment (0.003 mg/kg) was 0.001 mg/kg more than that found in fish. Average mean levels of these compounds followed the pattern-aldrin > dieldrin > endrin in sediment and aldrin > endrin > dieldrin in fish (Table 3). As studies have it, aldrin is readily broken down into dieldrin in plant and animal tissues or via photolysis to dieldrin in the environment (Akoto *et al.,* 2016; Akan *et al.,* 2014). In essence, the detection of dieldrin in the present study reflects the breakdown of aldrin by aquatic organisms or by photolysis and may signify past use of aldrin based pesticides within the Sankana locality. The high dieldrin levels may also be indicative of high rate of aldrin degradation in sediment. This observation agrees with that made by Kuranchie-Mensah *et al.* (2011) where low dieldrin levels were synonymous to low rate of aldrin degradation. Then and again, the detection of aldrin in fish was also suggestive of recent and possible continuous use of aldrin based pesticides within the study area despite its ban in Ghana. The average mean levels of aldrin and dieldrin recorded in fish and sediment in the present study were higher compared to mean aldrin and dieldrin levels reported by Darko *et al.* (2008) in their study on Lake Bosomtwi in the Ashanti region of Ghana. The present study also found the average mean levels of aldrin and dieldrin in fish to be lower than the levels found in sediment, agreeing with the findings of Darko *et al.* (2008). Similarly, average mean levels of aldrin and dieldrin attained for sediment in the present study were also relatively higher than mean

aldrin and dieldrin levels recorded in sediments by Kuranchie-Mensah *et al.* (2011). In the case of endrin however, average mean level recorded was below mean levels reported by Kuranchie-Mensah *et al.* (2011). Again, in the study by Kuranchie-Mensah *et al.* (2011), aldrin levels were comparatively higher than dieldrin which contrasts what was recorded in the present study. Unlike Akoto *et al.* (2016) that found no endrin residue in fish and sediment in their study, the present study detected endrin residues in fish and sediment. Average mean levels of aldrin and dieldrin detected in this study were above their respective established MRLs of 0.01 mg/kg, 0.05 mg/kg. Average mean level of endrin was however below its established MRL of 0.01 mg/kg.

p,p'-DDE and p,p'-DDD

Across the different sampling zones, *p,p'*-DDE was found present in only FS_D and SS_D while *p,p'*-DDD was present in only FS_D (Table 1;Table 2). Average mean level of *p,p'*-DDE in sediment comparatively was about 5.8-fold that in fish. *p,p'*-DDD on the contrary recorded an average mean concentration of 0.001 mg/kg in fish with sediment recording no *p,p'*-DDD (Table 3). *p,p'*-DDE and *p,p'*-DDD are both metabolites of *p,p'*-DDT and their detection in effect indicates photochemical or biological breakdown of the parent compound. *p,p'*-DDE and *p,p'*-DDD respectively result from the aerobic and anaerobic degradation of DDT. DDD to DDE ratios have been employed in many studies to indicate the pathway of DDT degradation. A DDD to DDE ratio less than 1 (< 1) is analogous to aerobic degradation whereas a DDD to DDE ratiohigher than 1 (> 1) indicative of anaerobic degradation (Unyimadu *et. al.,* 2018). On this premise it can be said that DDT degradation in fish and sediment both followed an aerobic pathway with a DDD to DDE ratio less than 1. As put forth by Akoto *et al.* (2016), the presence of these metabolites may typically suggest previous use of *p,p'*-DDT within the study area. No *p,p'*-DDD in sediment could typically be synonymous to complete degradation of the parent compound *p,p'*-DDT. Kuranchie-Mensah *et al.* (2011) found *p, p'*-DDE to be widespread in fish from the Volta Lake in Ghana. In the present study however, *p, p'*-DDE detection was limited to fish downstream of the studied dam. The present study corroborates the findings of Akoto *et al.* (2016), recording higher average mean levels of *p,p'*-DDE than *p,p'*-DDD in both fish and sediment. Mean levels of both residues in fish emerged higher than their respective levels in sediment in the study by Akoto *et al.* (2016). The average mean *p, p'*-DDE level in fish on the contrary was lower than the level found in sediment in respect of the present study. Average mean levels of *p, p'*-DDE and *p, p'*-DDD in fish were below the established MRL of 0.05 mg/kg. Average mean level of *p, p'*-DDE in sediment was however above the established MRL.

Endosulfan-A and B

Endosulfan-A was the sole OC residue detected in all fish and sediment samples found upstream, midstream and downstream of the Sankana dam. Endosulfan-B on the other hand was only present in SS_D (Table 1; Table2). Endosulfan-A levels detected in FS_U, FS_M and FS_D comparatively were higher than the respective levels detected in SS_U, SS_M and SS_D. Endosulfan-A levels in fish and sediment across the sampling zones followed the patterns $FS_D > FS_U > FS_M$ and $SS_D > SS_U > SS_M$ respectively. Mean levels of endosulfan-An in fish reflected an average mean that was 4-fold that in sediment. Average mean level of endosulfan-An in sediment was found to be 8-fold the level of endosulfan-B in sediment. Endosulfan is commercially available as a diastereomeric mixture of two biologically active isomers- alpha (A) and beta (B) in the ratio of 2:1 to 7:3 (Navarrete-Rodríguez *et al.,* 2016). The beta-isomer though more persistent than the alpha-isomer, has been demonstrated to be susceptible to conversion into the alpha-isomer while the reverse is impossible (Navarrete-Rodríguez *et al.,* 2016). The widespread detection and higher levels of endosulfan-A in fish and sediment as opposed to the lower levels of endosulfan-B in fish and sediment may not necessarily reflect recent use of the endosulfan pesticide. The higher mean levels of endosulfan-A in relation to B in both fish and sediment could result from the possible conversion of endosulfan-B to A. Darko *et al.* (2008) and Kafilzadeh (2015) both recorded the highest (total) endosulfan concentrations in sediment contrary to this study which recorded the highest endosulfan level in fish. They also found endosulfan mean level in sediment to be respectively 14 and 16 times the level in fish. In contrast, the present study recorded an average mean level of endosulfan-A in fish that was 4-fold that in sediment. Average mean levels of endosulfan-A and B in fish and sediment were below the established MRL of 0.05 mg/kg.

Methoxychlor, heptachlor and γ-chlordane

Methoxychlor was detected in FS_U, FS_D and SS_D while heptachlor manifested in FS_U, FS_M and SS_D. γ-chlordane like heptachlor was detected in FS_U and FS_M as well as in SS_M (Table 1; Table 2). These OC residues were thus quite prevalent in FS_U. In entirety, (average) mean levels of these pesticide residues were relatively higher in sediment than in fish. Methoxychlor, heptachlor and γ-chlordane average mean levels in sediment were respectively 1.5, 3.6 and 1.7-fold the levels found in fish. Prevalence of these OC residues in terms of average mean levels measured in fish and sediment followed the order methoxychlor > heptachlor > γ-chlordane contrary to the pattern evident in the study by Kuranchie-Mensah *et al.* (2011) where mean concentrations of same OC compounds detected in sediments (from different stations) followed the order γ-chlordane > heptachlor > methoxychlor. Kafilzadeh (2015) recorded slightly higher mean levels of heptachlor than γ-chlordane in sediment samples from Lake Tashk, consistent with the relatively higher heptachlor than γ-chlordane mean levels attained in this study. In the study by Akoto *et al.* (2016), methoxychlor, heptachlor and γ-chlordane in the Tono reservoir were at undetectable levels contrary to levels recorded for the Sankana dam in the present study. Average mean levels of methoxychlor, heptachlor and γ-chlordane in sediments all exceeded established MRL of 0.01 mg/kg in the present study. In fish however, only methoxychlor had an average mean level above the established MRL of 0.01 mg/kg.

CONCLUSION

The study revealed varying levels of 13 OC residues in the Sankana dam. Eleven (11) of such OC residues were detected in fish and twelve (12) in sediment. Total OC residue levels were relatively predominant upstream and downstream and least midstream. Prevalence in terms of number of OC residues identified per sampling zone followed the sequence $FS_D > FS_U > FS_M$ and $SS_D > SS_U > SS_M$ respectively for fish and sediment suggestive of a direct correlation between fish and sediment in relation to the different sampling zones. Average mean levels of β-HCH, γ-HCH, δ-HCH, endosulfan-A and *p,p'*-DDD residues in fish were relatively higher than the respective levels in sediment. β-HCH, γ-HCH, δ-HCH, endosulfan-A and *p,p'*-DDD average mean levels in fish were respectively 3.1, 3.0, 4.4, 4.0 and 10-fold the levels in sediment. *p,p'*-DDE,aldrin, dieldrin, endrin, methoxychlor, heptachlor, γ-chlordane and endosulfan-B on the other hand recorded relatively higher residual levels in sediment than in fish. Average mean levels of these residues approximately were respectively 5.8, 3.1, 230, 1.5, 1.5, 3.6, 1.7 and 10-fold the levels in fish. Approximately 53.8% of OC residues found in fish upstream exceeded their established MRLs. For fish found midstream and downstream, respectively 92.3 and 76.9% of OC residues detected were at levels below their established MRLs. Sediments obtained upstream, midstream and downstream respectively had 69.2, 84.5 and 53.8% of identified OC residues below their established MRLs. OC residues in the Sankana dam most likely emanated from nonpoint sources such as run-offs, drifts during spraying of nearby farmlands and from the disposal of pesticide wastes or their containers and washouts. Taking into account the fact that the Sankana dam serves as sources of irrigation water, drinking water and fish for the locals within the catchment area, the very presence of these OC residues (in fish and sediment of the dam) raises health concerns. These health concerns are heightened by the very tendency of these compounds to bio-accumulate in the fatty tissues of fish or be retained within the organic phase of sediments owing to their lipophilic-hydrophobic nature. The study essentially provides a baseline for continuous monitoring of OC contaminants in the Sankana dam and other water bodies upstream and downstream. The presence of some of the above OC residues at levels above their recommended MRLs typically suggests the possible recent and continuous use of OCPs within the catchment area. There is thus the need for relevant stakeholders to put measures in place and/or strengthen already existing policies that bans the importation, sale and use of OCPs by way of strict implementation or enforcement. There is also the need to sensitize surrounding communities on the adverse health effects likely to arise from the consumption of fish and water from the Sankana dam.

AUTHOR CONTRIBUTIONS

N.J. Mensah was the principal investigator, conceived the study idea, gathered literature, conducted experiments and compiled experimental data for manuscript preparation. S. Antwi-Akomeah

performed literature review, designed and conducted experiments, analyzed and interpreted the data and prepared the manuscript text. G.E. Sebiawu assisted the literature review, manuscript preparation and conduct of 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.

ABBREVIATIONS

HCH	Hexachlorocyclohexane
β-HCH	Beta-hexachlorocyclohexane
δ-HCH	Delta-hexachlorocyclohexane
γ-HCH	Gamma-hexachlorocyclohexane
ANOVA	Analysis ofvariance
C_2H_3N	Acetonitrile
$C_2H_3NaO_2$	Sodium acetate
CH_3COOH	Acetic acid
D	Downstream
eV	Electron volt
FAO	Food and agriculture organization
Fig.	Figure
FS	Fish samples
FS_D	Fish samples downstream
FS_M	Fish samples midstream
FS_U	Fish samples upstream
g	Gram
GC	Gas chromatography
GDP	Gross domestic product
km	Kilometer
KNUST	Kwame Nkrumah University of Science and Technology
M	Midstream
m	Meter
mg/kg	Milligram per kilogram
mg/mL	Milligram per milliliter
MgO_3Si	Magnesium silicate/florisil
$MgSO_4$	Anhydrous magnesium sulphate
Min.	Minutes
mL	Milliliter
mL/min	Milliliter per minute
mm	Millimeter
MRL	Maximum residue limit
MS	Mass spectrometer
$Na_3C_6H_5O_7$	Sodium citrate
Na_2SO_4	Sodium sulphate
ND	None detected
ng/g	Nanogram per gram
OC	Organochlorine
OCP	Organochlorine pesticide
OP	Organophosphorus
p,p'-DDE	Dichlorodiphenyldichloroethylene
p,p'-DDD	Dichlorodiphenyldichloroethane
rpm	Revolutions per minute
SD	Standard deviation
SIM	Selective ion monitoring
SS	Sediment samples
SS_D	Sediment samples downstream
SS_M	Sediment samples midstream
SS_U	Sediment samples upstream
TPM	Triphenylmethane
U	Upstream
v/v	Volume per volume
WHO	World health organization
WWF	World wildlife fund
µg/mL	Microgram per milliliter
µL	Microliter
µm	Micrometer

°C	Degrees Celsius
°C /min	Degrees celsius per minute
%	Percent
>	Greater than
<	Less than

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REVIEW PAPER

Increasing resident participation in waste management through intrinsic factors cultivation

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ABSTRACT

BACKGROUND AND OBJECTIVES: Resident participation in waste management is essential to overcome waste problems effectively. In many developing countries, the local government has been struggling to encourage resident involvement in the waste management process, but the participation rate is still low. Thus, it requires a system that can encourage residents to participate effectively and sustainably. Therefore, this study aimed to determine what determinant factors, either extrinsic or intrinsic, significantly improve resident participation by changing behaviour toward waste management.
METHODS: This study tried to get insights from previous studies about key determinant factors affecting resident behaviour toward waste management to improve participation, significantly using a literature review method.
FINDINGS: Educational setting for residents is crucial to improve waste management participation by cultivating key intrinsic factors with support from extrinsic factors that lead to changing behaviour. This study identified eight types of key contents shared in the educational setting to ensure its improvement. Key intrinsic factors should be cultivated, including six kinds of knowledge and five emotional domain factors. The six critical types of knowledge include technical experience, waste management performance knowledge, perception of benefits, environmental awareness, understanding of individual and social responsibility, and understanding the social norms and regulations. The five intrinsic factors in the emotional domain include environmental efficacy, motivation, personal moral norms, PBC, and Attitude toward waste management. All the critical determinant factors, including intrinsic and extrinsic factors, should support each other to improve residents' behaviour, leading to sustainable participation.
CONCLUSION: Relevance of educational content to the residents is crucial to ensure educational intervention effectiveness. With full support from the antecedent factors, waste management behaviour can be nurtured sustainably, significantly increasing the participation rate. Combining extrinsic and intrinsic factors is recommended to ensure the effectiveness of the improvement of resident participation.

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INTRODUCTION

The accumulation of municipal waste generation is one of the main problems in every country throughout the world. Its number keeps increasing parallel with population growth, urbanization, industrialization, and economic growth (Borongan and Okumura, 2010). The waste generation will increase up to 70% from 2016 to 2050 due to massive population growth and urbanization (World Bank, 2018). Household waste commonly dominates compositional characteristics of Municipal Solid Waste (MSW) (Aleluia and Ferrão, 2016), presented by a high percentage of vegetable and food waste in the MSW composition. Table 1 shows some examples of compositional characteristics of MSW in several developing countries.

Due to their contribution to the domination of MSW, residents become one of the critical stakeholders in the waste management process (Kamaruddin *et al.*, 2017; Owamah *et al.*, 2017). Residents play various roles in the waste management process, including waste reduction (Abbasi, 2018), waste separation at source (Areeprasert *et al.*, 2018; Heidari *et al.*, 2018; Boonrod *et al.*, 2019; Priti and Mandal, 2019), and waste recycling (Kamaruddin *et al.*, 2017; Ma *et al.*, 2018). Moreover, 3 R (Reuse, Reduce, Recycle) is the most preferred solution for diverse countries due to its effectiveness in controlling waste generation (Borongan and Okumura, 2010; Modak *et al.*, 2016). Therefore, encouraging resident participation is vital (Mukama *et al.*, 2016; Song *et al.*, 2016; Sekito *et al.*, 2018) for sustainable waste management (Kawai *et al.*, 2016; Ma *et al.*, 2018; Boonrod *et al.*, 2019). Resident participation can succeed in the waste management system in many countries (Zahra *et al.*, 2012; Nmere *et al.*, 2020). Even though it is vital to involve residents in waste management process from the source, resident participation in developing countries is mostly lacking, far behind developed countries. Banerjee and Sarkhel (2019) found that 60% of cities from developed countries practice more complicated separation at source, while 87 % of cities in developing countries mix their waste and rely on authorities to handle it, implying gaps in various aspects of the waste management system (Marshall and Farahbakhsh, 2013). Furthermore, only about 20% of cities in the developing countries can process the waste further, showing a lack of knowledge and skill on waste management (Borongan and Okumura, 2010; Banerjee and Sarkhel, 2019). Thus, developing countries are still struggling in improving waste participation, especially in separation at the source step. Local governments in developing countries should find effective ways to encourage resident participation, not only on the waste separation but also in waste reduction and recycling (Kawai *et al.*, 2016). To find the strategies, it is not merely by adopting the system implemented in developed countries due to its difference in the context. Instead, there should be some consideration toward various factors, including residents' characteristics, economic, cultural, and so forth (Kawai *et al.*, 2016). Some studies showed that most developing countries relied on extrinsic strategies as the determinant factors to encourage participation and improve their behaviour toward waste management. For instance, the extrinsic approaches are policy enforcement (Heidari *et al.*, 2018; Ma *et al.*, 2018; Putri *et al.*, 2018), incentives

Table 1: MSW compositional characteristics from various cities in developing countries

Composition	Esmaeilizadeh *et al.* (2020) (Iran)	Speier *et al.* (2018) (Bangalore City, India)	Sekito *et al.* (2018) (Malang City, Indonesia)	Xu *et al.* (2016) (Xiamen, China)	Laohalidanond *et al.* (2015) (Bangkok, Thailand)
Vegetable and food waste	68,40%	56,43%	41,00%	66,19%	49,90%
Paper/cardboard	7,31%	7,67%	8,50%	9,89%	8,50%
Plastics	9,80%	8,50%	26,00%	13,17%	28,50%
PET (plastic bottle)	0,99%	-	-	-	-
Metal	1,59%	0,23%	3,60%	1,06%	1,40%
Rubber	1,09%	-	-	-	-
Textile	3,02%	4%	6%	4,38%	5,20%
Glass	2,33%	1,27%	-	3,61%	4,40%
Wood/leaves	0,97%	0,33%	9,20%	0,6%	-
Others	4,48%	21,47%	6,00%	1,10%	2,10%

as an economic motivation, and infrastructure improvement (Sari and Umanto, 2014; Putri *et al.*, 2018). However, external factors play fewer roles in changing waste management behaviour (Eneji *et al.*, 2019). These extrinsic factors cannot make a sustainable change in residents' behaviour toward waste management (Issock *et al.*, 2020), although it is more impactful for developed countries (Musella *et al.*, 2018; Mintz *et al.*, 2019). More studies are required to determine what strategies are best suited to motivate residents to participate by changing their waste management behaviour sustainably (Knickmeyer, 2019). Education is the best intervention to change people's awareness of waste management and encourage them to be involved (Chow *et al.*, 2017; Lee *et al.*, 2018; Setiawan *et al.*, 2019; So *et al.*, 2019). Education becomes the platform to share facts, information, and values for the targeted community to change behaviour through intrinsic factors in the personal domain (Stern, 1999). When intrinsic factors are pro to the waste management system, the residents will participate in the waste management process (Liao *et al.*, 2018). On the contrary, when the educational method is ineffective, it will cause problems in the waste management system (Esmaeilizadeh *et al.*, 2020). Moreover, the type of facts, information, and values being shared in education determine what intrinsic factors will be nurtured in the individuals (Janmaimool and Denpaiboon, 2016), implying that the contents play a role in determining whether education is adequate to encourage changing behaviour or not. However, studies focusing on what contents should be shared within education for the residents are rarely available. Besides, studies focusing on identifying vital intrinsic factors that should be nurtured through education are also scarce. Therefore, the objectives of the study are to figure out what key intrinsic factors play roles in improving waste management behaviour and map the contents that should be shared to nurture the key intrinsic factors. This study also identified the role of extrinsic factors to support the changing behaviour effort. Eventually, it is proposed a model that shows the relationship among the critical factors, including intrinsic and extrinsic, to change waste management behaviour. This study is a part of a doctoral dissertation titled as The implementation of knowledge management for waste management behaviour Improvement carried out at Institut Teknologi Bandung, Bandung City, Indonesia during 2019 – 2021.

MATERIALS AND METHODS

The study consists of a literature review discussing determinant factors (intrinsic and extrinsic) affecting resident participation improvement mainly in developing countries, with a unit of analysis on adults including households, public community, and academic students. This study's unit of analysis is the household, considering that adults are more dominant in dealing with waste management at the household level. The review studies included journal articles discussing waste management behaviour of residents in developing countries published in the English Language between 2015–2020 to ensure its relevance. The database sources were mainly from ScienceDirect and Proquest as the primary database, while some papers were from Mendeley, ResearchGate, and Semantic. For literature searching, this study used the basic concept of waste management behaviour where the resident involved. The term waste management in this study refers to MSW (Benešová *et al.*, 2010), in which waste generator is mainly from households (Aleluia and Ferrão, 2016). Therefore, their participation is crucial to improve the waste management system (Modak *et al.*, 2016). Waste management behaviour refers to all actions where residents must involve in the waste management process, including waste separation, waste reduction, waste recycling, waste reuse, and waste disposal behaviour (Sukholthaman *et al.*, 2017). The behaviours required in 3R are waste reduction behaviour, waste separation behaviour, waste recycling behaviour, and the combination of those behaviours. Then the Keywords used are "*waste management behavio**", "*determinant factors*", "*social factors*", "*waste separation*", "*waste reduction behavio**", "*waste recycling behavio**", "*waste minimi**", "*waste segregation behavio**", "*waste sorting behavio**", "*resident participation*", "*household participation*, "*developing countries*", and the combination among the keywords to get the most relevant papers. To ensure its quality and reproducibility, the research methodology process is based on Fink (2014), as presented in Fig. 1. This study used the NVIVO R1 tool to help the review process and map the content. The 2-3-4 processes are iterative, applying feed-back iteration to clarify the literature

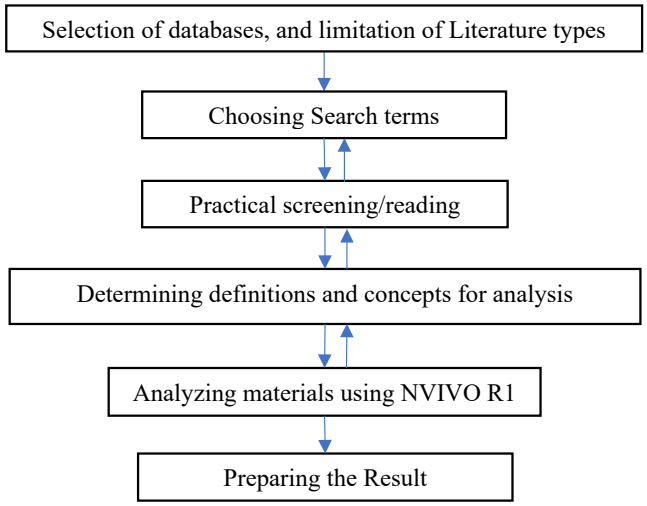

Fig. 1: The Literature Review Process (Fink, 2014)

exploration and to define the inquiry (Zacho and Mosgaard, 2016). After the assessment, 68 studies discussed determinant factors, including intrinsic and extrinsic factors affecting resident behaviour to waste management, and 38 studies identifying important contents in the education intended for resident participation improvement. According to the initial findings, the definition and concept for the content analysis process was determined.

The basic concept adopted as the framework of the study is the idea of environmental-behavioural science by Stern (1999). In environmental, behavioural science, Stern (1999) grouped the domains into three: personal/intrinsic domain, behavioural domain, and contextual/extrinsic domain. Intrinsic factors are the determinant factors from an internal or personal mind that play a role in determining individual behaviour, such as personal beliefs, moral normative, social obligations, attitude, and so forth. Behavioural domains are factors representing the intervention's effect, including activities, participation, behaviour, and habits. In behavioural change, the theories commonly focus on determinant factors influence behaviour intrinsically and recognize extrinsic factors intervening (Turaga *et al.*, 2010). According to Stern (1999), Environmental-based behaviour can be changed by giving intervention (extrinsic factors) to intervene intrinsic factors such as providing information or education system, policy or regulation, economic variables including demographic factors such as age, income, education level, and so forth. Both extrinsic and intrinsic factors affecting the behavioural domain are considered determinant factors. However, demographic characteristics in this study are excluded from the discussion due to the limitation of time and space. The analytical framework was used for initial coding, and the axial coding emerged from the analysis process. The framework analysis of this study is presented in Table 2.

Table 2: The analytical framework to guide the content analysis

No	Categories	Sub-categories	Specification
1	Determinant factors	Intrinsic factors	• All intrinsic factors affecting waste management behaviour significantly • All educational contents including facts, information and values required to nurture intrinsic factors
2		Extrinsic factors	All extrinsic factors intervening intrinsic factors that affecting waste management behaviour significantly
3	Behavioural domain	Waste management behaviour	Waste reduction behaviour waste separation behaviour waste recycling behaviour

Table 3: References focusing on identifying various determinant factors as the antecedents of waste management behaviour of residents in developing countries

No	Countries	Intrinsic factors	Extrinsic factors	Unit of analysis	References
1	China	√	√	Households	Song *et al.* (2016)
2	China	√	√	Households	Yuan *et al.* (2016)
3	China	√	√	Households	Li *et al.* (2017)
4	China	√	√	Households	Xu *et al.* (2017)
5	China	√	√	Households	Xiao *et al.* (2017)
6	China	√	√	Households	Ma *et al.* (2018)
7	China		√	Households	Meng *et al.* (2018)
8	China	√	√	Households	Liao *et al.* (2018)
9	China	√		Households	Xu *et al.* (2018)
10	China	√	√	Households	Fan *et al.* (2019)
11	China	√	√	Households	Liu *et al.* (2019)
12	China	√	√	Households	Meng *et al.* (2019)
13	China	√	√	Households	Zhang *et al.* (2019)
14	China	√	√	Households	Wang *et al.* (2020a)
15	China	√	√	Households	Wang *et al.* (2020b)
16	China	√	√	Households	Wang and Hao *et al.* (2020)
17	China	√	√	Households	Ma *et al.* (2020)
18	Columbia	√	√	Households	Padilla and Trujillo (2018)
19	Egypt	√		Households	Abdelradi, (2018)
20	Ghana	√	√	Households	Oduro-Kwarteng *et al.* (2016)
21	Ghana	√	√	Households	Addo *et al.* (2017)
22	Ghana	√	√	Households	Gyimah *et al.* (2019)
23	Ghana	√	√	Households	Alhassan *et al.* (2020)
24	Guinea		√	Households	Mamady, (2016)
25	Hongkong	√	√	Households	Yeung and Chung (2018)
26	India	√	√	Households	Wadehra and Mishra (2018)
27	Indonesia	√		Public Community	Ramadan *et al.* (2016)
28	Indonesia	√	√	Households	Trihadiningrum *et al.* (2017)
29	Indonesia	√		Households	Maryati *et al.* (2018)
30	Indonesia		√	Households	Putri *et al.* (2018)
31	Indonesia	√	√	Households	Sekito *et al.* (2018)
32	Indonesia	√	√	Households	Ulhasanah and Goto (2018)
33	Indonesia		√	Households	Setiawan *et al.* (2019)
34	Indonesia	√	√	Households	Pasaribu *et al.* (2020)
35	Indonesia	√	√	Households	Setiawan (2020)
36	Iraq	√		Households	Abdulredha *et al.* (2020)
37	Iran	√		Households	Astane and Hajilo. (2017)
38	Iran	√	√	University Students	Heidari *et al.* (2018)
39	Iran	√	√	Households	Almasi *et al.* (2019)
40	Jordan	√	√	Academy Students	Elayan and Ibrawish. (2017)
41	Malaysia	√	√	Households	Tiew *et al.* (2015a)
42	Malaysia	√		Academy Students	Ayob *et al.* (2017)
43	Malaysia	√	√	Households	Choon *et al.* (2017)
44	Malaysia	√	√	Households	Al-Naggar *et al.* (2019)
45	Malaysia	√	√	Households	Sujata *et al.* (2019)
46	Nicaragua		√	Households	Hartmann, (2018)
47	Nigeria		√	Households	Idamah, (2015)
48	Nigeria		√	Households	Nnaji, (2015)
49	Nigeria		√	Households	Nmere *et al.* (2020)
50	Pakistan		√	Households	Akhtar *et al.* (2017)
51	Palestine	√	√	Households	Al-khateeb *et al.* (2017)
52	Palestine	√	√	Households	Kattoua *et al.* (2019)
53	Palestine	√	√	Households	Salem *et al.* (2020)
54	Philippine	√		Households	Limon *et al.* (2020)
55	Thailand		√	Households	Navykarn and Muneenam, (2015)
56	Thailand	√	√	Households	Janmaimool and Denpaiboon, (2016)
57	Thailand	√	√	Households	Yukalang *et al.* (2017)
58	Thailand	√		Households	Boonrod *et al.* (2019)
59	Thailand		√	Households	Wichai-utcha and Chavalparit, (2019)
60	Trinidad & Tobago	√	√	Households	Lawrence *et al.* (2020)
61	UAE	√	√	School Students	Hammami *et al.* (2017)
62	Uganda	√	√	Households	Mukama *et al.* (2016)
63	Uganda		√	Households	Fredrick *et al.* (2018)
64	Vietnam	√	√	Households	Loan *et al.* (2017)
65	Vietnam	√		Households	Nguyen and Watanabe, (2019)
66	Vietnam		√	Households	Singer *et al.* (2019)
67	South Africa	√	√	Households	Issock *et al.* (2020)
Total Number of papers		54	57		

Table 4: Identified intrinsic factors affecting waste management behaviour

No.	Intrinsic factors	Waste reduction behaviour	Waste separation behaviour	Waste recycle behaviour	Waste management behaviour	Number of papers
1	Knowledge	√	√	√	√	28
2	Attitude to waste management	√	√	√	√	28
3	Environmental awareness	√	√	√	√	23
4	Perceived behavioural control (PBC)	√	√	√		21
5	Intention		√	√	√	15
6	Personal moral norms		√	√	√	15
7	Perception of benefits		√	√		9
8	Subjective norms		√	√		9
9	Environmental efficacy		√		√	8
10	Habits		√			6
11	Intrinsic motivation		√	√		5
12	Trust to local authorities		√			6
13	Lifestyle	√				1

The 67 identified papers that discussed determinant factors, including intrinsic and extrinsic factors affecting household waste management behaviour in developing countries, are presented in Table 3. Among 67 articles, 54 articles identified intrinsic factors, while 57 articles identified extrinsic factors. The discussion of each factor will be more explored in the next subsection.

Intrinsic factors affecting waste management behaviour

Among 54 papers discussing intrinsic factors affecting residents' waste management behaviour in developing countries, there are 13 intrinsic factors identified. All the identified intrinsic factors are presented in Table 4.

Knowledge

According to Table 4, knowledge is to be the most mentioned factors that affect all waste management behaviour being studied, including waste reduction behaviour (Astane and Hajilo, 2017), waste separation behaviour (Oduro-Kwarteng *et al.*, 2016; Ramadan *et al.*, 2016; Choon *et al.*, 2017; Trihadiningrum *et al.*, 2017; Xiao *et al.*, 2017; Xu *et al.*, 2017; Ulhasanah and Goto, 2018; Boonrod *et al.*, 2019; Fan *et al.*, 2019; Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Alhassan *et al.*, 2020; Wang *et al.*, 2020b), waste recycling behaviour (Elayan and Ibrawish, 2017; Hammami *et al.*, 2017; Trihadiningrum *et al.*, 2017; Yeung and Chung, 2018; Almasi *et al.*, 2019; Wang *et al.*, 2020a) and waste management behaviour in general (Janmaimool and Denpaiboon, 2016; Addo *et al.*, 2017; Maryati *et al.*, 2018; Al-Naggar *et al.*, 2019; Almasi *et al.*, 2019; Meng *et al.*, 2019; Pasaribu *et al.*, 2020). Some studies indicated the importance of knowledge acquisition toward residents before they participate in the waste management process. Environmental knowledge has a role in determining the degree of intention to separate in Indonesia (Ulhasanah and Goto, 2018). Knowledge related to health impact influenced positive belief of households in Luzon Region, the Philippines, toward waste management (Limon *et al.*, 2020), while lack of its knowledge caused low participation in various other countries such as Malaysia (Al-Naggar *et al.*, 2019), Thailand (Boonrod *et al.*, 2019) and China (Meng *et al.*, 2019). Technical knowledge toward waste sorting (Choon *et al.*, 2017; Almasi *et al.*, 2019; Fan *et al.*, 2019; Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Wang *et al.*, 2020b) or waste recycling technique (Xiao *et al.*, 2017; Meng *et al.*, 2019) was also proven to affect resident participation toward waste management. Lack of technical experience caused reluctance to practice the waste management process in Indonesia due to overthinking the difficulty, which may burden the households (Sekito *et al.*, 2018). Besides, when investigating factors affecting waste generation behaviour in Zanjan Province, Iran, Astane and Hajilo (2017) argued that possessing indigenous knowledge on the material use efficiency was vital in waste reduction. Even though some knowledge varieties are identified to be an influential factor for waste management behaviour, some studies found vice versa. The study conducted by Pasaribu *et al.* (2020) and Wang *et al.* (2020a)

found that knowledge was not significantly affecting intention and behaviour toward waste management, especially waste recycling. The reason can be due to information being shared was not relevant to encourage the residents toward waste management behaviour, as implied by two studies which indicated that correct knowledge affected its successfulness in changing the expected behaviour of households in Thailand (Janmaimool and Denpaibon, 2016) and Hong Kong (Yeung and Chung, 2018). Other proofs are such as the study conducted by Trihadiningrum *et al.* (2017). They found that knowledge related to the effect of solid waste toward GHG emission did not correlate Indonesian households' participation to waste separation. While the study about behaviour toward waste generation and separation in Ghana conducted by Addo *et al.* (2017) in 2016 found that moderate knowledge related to the consequence of improper waste management to health could not encourage the residents to direct practice. On the other hand, knowledge about the correlation between waste management and environmental problems significantly affected residents' attitudes in Sharjah city, UAE (Hammami *et al.*, 2017) and Kermanshah City, Iran (Almasi *et al.*, 2019). Such knowledge eventually nurtured their willingness to influence others and increased participation in waste segregation in Delhi, India (Wadehra and Mishra, 2018). It indicates that waste management behaviour requires specific information shared with the residents (Xu *et al.*, 2017). Certain information correlates with certain intrinsic factors required to improve intention and behaviour (Hammami *et al.*, 2017). As indicated by Wang *et al.* (2020a), it seemed a certain type of knowledge was required by households in 10 urban cities in China to nurture awareness, attitude, and personal moral norms. However, Oduro-Kwarteng *et al.* (2016) argued that technical separation knowledge would be able to improve motivation to do the separation, according to their study to investigate waste separation behaviour of households in Kumasi Metropolis, Ghana. So, the power of knowledge is stronger to affect intention and behaviour toward waste management, especially if the behaviour seems to burden, like recycling activities. Moreover, relevance to the type of information to improve knowledge is also crucial to pay attention to. The knowledge is supposed to address the relevant problems experienced by the residents (Knickmeyer, 2019). Thus, it should be chosen knowledge relevant to the residents where the education is conducted to ensure its effectiveness. Besides, external factors may also involve in strengthening or loosening the willingness to involve in the waste management practice, as indicated by Almasi *et al.* (2019), who reported that the primary cause of recycling practice absence in Kermanshah City, Iran according to the study in 2016 was due to lack of sufficient infrastructures.

Attitude to waste management

Attitude is a positive stance toward waste management due to various reasons, including environmental reasoning (Choon *et al.*, 2017). Attitude is another intrinsic factor, besides knowledge, which influence all of the behaviour related to waste management, including waste reduction behaviour (Astane and Hajilo, 2017), waste separation behaviour (Mukama *et al.*, 2016; Yuan *et al.*, 2016; Ayob *et al.*, 2017; Choon *et al.*, 2017; Loan *et al.*, 2017; Xu *et al.*, 2017; Heidari *et al.*, 2018; Liao *et al.*, 2018; Padilla and Trujillo, 2018; Liu *et al.*, 2019; Gyimah *et al.*, 2019; Nguyen and Watanabe, 2019; Zhang *et al.*, 2019; Alhassan *et al.*, 2020; Wang *et al.*, 2020b), waste recycle behaviour (Elayan and Ibrawish, 2017) and waste management behaviour in general (Addo *et al.*, 2017; Yukalang *et al.*, 2017; Almasi *et al.*, 2019; Meng *et al.*, 2019; Pasaribu *et al.*, 2020). Most studies found that attitude and knowledge became a critical factor in waste reduction and waste separation behaviour in various countries. Attitude correlated to the knowledge of households in Kermanshah City, Iran (Almasi *et al.*, 2019) and Hi'an, China (Liu *et al.*, 2019) while it also became vital factors directly affecting waste management behaviour of households in Iran (Astane and Hajilo, 2017), China (Liao *et al.*, 2018; Meng *et al.*, 2019), Ghana (Alhassan *et al.*, 2020), Trinidad & Tobago (Lawrence *et al.*, 2020), and academic students in Jordan (Elayan and Ibrawish, 2017). A negative attitude toward waste management became a barrier to waste management in Thailand (Yukalang *et al.*, 2017). The representation of negative attitude is such as lack of environmental concern, disbelief to the solvability of waste problems, and blaming other people due to lack of personal responsibility (Yukalang *et al.*, 2017; Liu *et al.*, 2019). It indicated that attitude is built based on environmental

awareness, environmental efficacy, and personal moral norms. For environmental efficacy, Ayob *et al.* (2017) and Elayan and Ebrawish (2017) contended that university students are likely to practice waste separation if they are sure that their actions contribute to pollution reduction and a clean environment. It implies that attitude is affected by their knowledge toward environmental conservation, which affects their environmental efficacy. The study conducted by Gyimah *et al.* (2019), which aimed at examining waste separation practice of Cape Coast Metropolis households in Ghana in 2016, indicated that attitude was also affected by knowledge toward health impacts, perception of time availability, facilities, and technical knowledge toward waste separation. While Nguyen and Watanabe (2019) contended that the positive attitude of residents in Vietnam toward waste separation was motivated by perceived benefits they got from the activities. Also, Ma *et al.* (2018) found that residents' pro-environmental attitudes in rural China was positively correlated to regulation. In this case, Ma *et al.* (2018) and Almasi *et al.* (2019) argued that external factors would be more influential when awareness of the environment is low, indicating the importance of waste separation awareness. Addo *et al.* (2017), Xu *et al.* (2017), and Almasi *et al.* (2019) also found no significant effect of attitude to waste separation intention of households. Meanwhile, Yuan *et al.* (2016) found that attitude toward waste separation behaviour negatively affected residents' waste separation behaviour in Beijing City. Yuan *et al.* (2016) explained this contrary phenomenon as resistance to change their habits. Further, they stated that household waste in Beijing was excluded from the separation program, and residents' attitudes toward separation were prepared for willingness to pay. It means that the separation process was not conducted by themselves but by the authorities. Also, it was not their habits to involve household waste into separation. Also, the study conducted in two Slums, Central Uganda (Mukama *et al.*, 2016) and the study about residents' separation behaviour in Taiyuan City, China (Liu *et al.*, 2019) indicated the role of personal and social responsibility to improve attitude through improving the residents' awareness. Personal responsibility results in personal moral norms, together with attitude, affected Anhui Province residents' intention toward waste separation in China (Wang *et al.*, 2020b). Social responsibility is supposed to raise subjective norms, which is in line with the finding of the study conducted in Hangzhou city, China, by Xu *et al.* (2017). Personal moral norms are highly required to build a powerful attitude to complement subjective norms (Liu *et al.*, 2019) because attitude is operationalized through personal feeling toward the intended action (Xu *et al.*, 2017; Zhang *et al.*, 2019). It means that subjective norms that are considered external enforcement are not enough to solely raise personal moral norms (Xu *et al.*, 2017). Consequently, a strong and intensive educational program is required to improve both knowledge and attitude (Yeung and Chung, 2018; Padilla and Trujillo, 2018; Liu *et al.*, 2019).

Environmental awareness

According to Table 4, environmental awareness becomes the third most dominant intrinsic factor mentioned by all references. It implies that awareness must be a crucial intrinsic factor for residents in developing countries to encourage waste management participation. It includes waste reduction (Abdelradi, 2018), waste separation (Janmaimool and Denpaiboon, 2016; Mukama *et al.*, 2016; Oduro-Kwarteng *et al.*, 2016; Song *et al.*, 2016; Yuan *et al.*, 2016; Trihadiningrum *et al.*, 2017; Ulhasanah and Goto, 2018; Heidari *et al.*, 2018; Fan *et al.*, 2019; Kattoua *et al.*, 2019; Nguyen and Watanabe, 2019; Zhang *et al.*, 2019; Limon *et al.*, 2020), waste recycling (Al-Khateeb *et al.*, 2017; Elayan and Ibrawish, 2017; Heidari *et al.*, 2018; Yeung and Chung, 2018; Abdulredha *et al.*, 2020; Wang *et al.*, 2020a) or waste management in general (Almasi *et al.*, 2019; Meng *et al.*, 2019). Environmental awareness is also identified as the driver of waste management participation in developed countries (Kokkinos *et al.*, 2019; Elkiran et al., 2018). Awareness becomes pivotal because it is the primary step to change personal behaviour by influencing its attitude, leading to a willingness to change. For example, the findings from the studies about waste management behaviour of households conducted in Sharjah City, UAE (Hammami *et al.*, 2017), Padang city, Indonesia (Ulhasanah and Goto, 2018) and in Macau, China (Song *et al.*, 2016) which showed the vital role of awareness. When evaluating determinant factors of waste management behaviour conducted in Rayong Province, Thailand in 2016, Janmaimool and Denpaiboon (2016) found that environmental awareness was mediated by

environmental efficacy to affect their decision to participate in the waste management process. The individual should realize their capability to contribute to environmental improvement to some extent (Janmaimool and Denpaiboon, 2016). The study in Kerbala City, Iran in 2016 (Abdulredha *et al.*, 2020), two Slums, Central Uganda (Mukama *et al.*, 2016), and Macau residents in 2011 (Song *et al.*, 2016), proved that improving people's awareness toward proper waste management process influenced the effectiveness of waste management system. Lack of environmental awareness was a barrier to waste recycling practice in two districts in Palestine (Kattoua *et al.*, 2019). A study conducted by Heidari *et al.* (2018) toward students at Ferdowsi University, Iran, in 2016 showed that awareness affected waste separation intention toward attitude and personal moral norms. This finding is agreed by Zhang *et al.* (2019), who investigated the waste separation behaviour of households in China. Zhang *et al.* (2019) showed that awareness would influence intention through personal attitude and personal moral norms. In this study, attitude is considered as the personal moral norms itself. In relation to participation, Trihadiningrum *et al.* (2017) found that 40% of residents involved in their study in Surabaya City, Indonesia stated that their reason to be involved in the waste separation activities was their awareness of the environment. Environmental awareness was also proven to affect residents' waste separation behaviour in China (Choon *et al.*, 2017; Fan *et al.*, 2019) and Vietnam (Nguyen and Watanabe, 2019). On the other hand, low environmental awareness was to be the main reason for the absence of participation in waste separation in Macau residents (Song *et al.*, 2016). Insufficient understanding of the impact of human activities toward their environment might be the cause, as indicated by the studies conducted in China in 2011 (Song *et al.*, 2016), Shanghai in 2014 (Fan *et al.*, 2019), Thailand in 2016 (Janmaimool and Denpaiboon, 2016), and Iran in 2016 (Heidari *et al.*, 2018). To nurture environmental Awareness, Janmaimool and Denpaiboon (2016), Yuan *et al.* (2016), Loan *et al.* (2017), Ulhasanah and Goto (2018), and Salem *et al.* (2020) suggested improvement on understanding toward the impacts of waste problems and the significance of the waste management practice toward environmental quality. Similarly, Abdelradi (2018) indicated that understanding food waste impacts and religious beliefs would improve residents' environmental awareness in Cairo, Egypt. Besides, Gyimah *et al.* (2019), Limon *et al.* (2020), and Salem *et al.* (2020) also suggested residents to understand waste impacts on human health for awareness improvement. Furthermore, Abdelradi (2018) and Tiew *et al.* (2015a) showed that religious beliefs could be impactful to improve environmental awareness through understanding the personal responsibility of protecting the environment (Mohamad *et al.*, 2012). This is in line with the idea from Stern *et al.* (1999) who contended that religious view probably had crucial influence to environmentalism. Nevertheless, Xu *et al.* (2016) found that religious beliefs negatively affected residents' waste generation behaviour in Xiamen Island, China. Unfortunately, there is no information about what questions were given by Xu *et al.* (2016) to measure the religious beliefs on their study, so it cannot be compared to the results to the studies conducted by Abdelradi (2018), Tiew *et al.* (2015a) and Mohamad *et al.* (2012) which showed the contrary result. In the case of religious belief influence toward environmental awareness, it seemed not to depend on the religious affiliation (Addo *et al.*, 2017; Al-Naggar *et al.*, 2019). Mohamad *et al.* (2012) found that the value of environmental awareness is impactful on various religious communities in Malaysia such as Beautiful Gates (Christianity), Tzu Chi Association (Buddhism), Surau Al-Husna (Islam), and also Batu Caves Temple (Hinduism). The influence is more likely to be the effects of implementation toward ethical and spiritual value being taught by the religions concerning environmental conservation and charity intention (Al-khatib *et al.*, 2009). Eventually, religious-based ethics and values can be included to enrich educational contents to increase environmental awareness.

Perceived behavioural control (PBC)

PBC refers to individual perception toward their capacity and possibility in conducting a particular behaviour by considering obstacles and resources supporting the expected behaviour such as the availability of time, space and facilities, convenience in doing the activities, and also their confidence in technical knowledge related to the behaviour (Xu *et al.*, 2017; Sujata *et al.*, 2019). Even though many studies considered PBC and Self-efficacy as different

constructs, Ajzen viewed these two constructs are similar because PBC consists of self-efficacy and controllability toward the intended behaviour (Sujata *et al.*, 2019). Among waste management behaviour being studied in the previous studies, PBC was dominantly investigated in studies related to waste separation behaviour. The reasons can be due to the less popularity of the recycling activity in developing countries because they are commonly encouraged to conduct waste separation. In contrast, recycling is handled by the authorities (Marshall and Farahbakhsh, 2013). On the other hand, recycling activity is commonly related to waste separation to valuable inorganic waste being sold, which does not require any treatment in advance. PBC was proven to be significant in affecting waste separation behaviour of residents in various cities in China (Yuan *et al.*, 2016; Xu *et al.*, 2017, 2018; Wang *et al.*, 2020b), residents in Ghana Millenium City (Alhassan *et al.*, 2020) and also university students in University Teknologi Malaysia (Ayob *et al.*, 2017). The main reason of perception that affected their intention to conduct waste separation is perceived time availability (Song *et al.*, 2016; Choon *et al.*, 2017; Trihadiningrum *et al.*, 2017; Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Loan *et al.*, 2017; Alhassan *et al.*, 2020; Setiawan, 2020; Ma *et al.*, 2020). Also, the perception toward time cost-burdened the residents in Klang Valley, Malaysia (Choon *et al.*, 2017) and residents in Surabaya City, Indonesia (Trihadiningrum *et al.*, 2017), causing laziness to change their past behaviour. It can be the indication that they perceived waste separation to be not easy to do (Ramadan *et al.*, 2016; Trihadiningrum *et al.*, 2017; Xiao *et al.*, 2017; Heidari *et al.*, 2018; Sekito *et al.*, 2018; Ma *et al.*, 2020). When residents think the waste separation procedure is easy, they tend to do it. Similarly, when they believe it is hard to do the separation, they tend to leave it (Choon *et al.*, 2017). Moreover, Trihadiningrum *et al.* (2017) contended that a lack of environmental concern might cause laziness toward waste separation. Besides time availability and perceived difficulty, space, as well as facilities availability, also affected residents' PBC, which eventually affect their behaviour toward waste separation as shown by the findings from various studies (Loan *et al.*, 2017; Trihadiningrum *et al.*, 2017; Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Sujata *et al.*, 2019; Alhassan *et al.*, 2020). However, the study conducted by Xu *et al.* (2017) and Zhang *et al.* (2019) showed an insignificant effect of PBC on intention in China. It can be because their behaviour toward waste separation was more influenced by subjective norms and past behaviour, instead of their capability and convenience to do it (Zhang *et al.*, 2019). It implies that regardless of their perception of their incapability in doing waste separation, they may still conduct it because it has been their habit and becomes their social culture. As a result, they may practice improperly. Accordingly, to improve PBC toward waste management behaviour, Choon *et al.* (2017) suggested that Malaysian authorities make sure that their residents have sufficient knowledge toward simple waste separation methods to lessen residents' reluctance to do the separation. Similarly, when investigating Waste Bank as a communal-based recycling system implemented in Malang City, Indonesia, in 2013, Sekito *et al.* (2018) suggested more simplicity on the separation process to elevate residents' motivation to participate. Furthermore, Liu *et al.* (2019) and Xu *et al.* (2018) suggested external factor completion such as availability of facilities, while Yuan *et al.* (2016) recommended raising resident's consciousness toward their responsibility toward waste problems to support the formation of PBC. Furthermore, personalised feedback in the form of exposure toward recyclable implementation and monitoring data dissemination is also required (Fan *et al.*, 2019; Xu *et al.*, 2018), to improve their confidence toward their capacity in implementing waste management (Wang *et al.*, 2020b; Xu *et al.*, 2018).

Intention

The intention factor is discussed mainly in the studies focusing on waste separation behaviour (Janmaimool and Denpaiboon, 2016; Mukama *et al.*, 2016; Song *et al.*, 2016; Xu *et al.*, 2017; Heidari *et al.*, 2018; Liao *et al.*, 2018; Sekito *et al.*, 2018; Ulhasanah and Goto, 2018; Fan *et al.*, 2019; Gyimah *et al.*, 2019; Issock *et al.*, 2020; Wang *et al.*, 2020b), while only two studies are investigating about waste recycling behaviour (Elayan and Ibrawish, 2017; Wang *et al.*, 2020a). Although the study by Sekito *et al.* (2018) focused on recycling behaviour in Indonesia, they investigated the intention to separate waste, which proved crucial to encourage people to conduct recycling. It is understandable since waste separation is the beginning process before waste is recycled. The

intention is often considered similar to motivation, which represents individual willingness or motivation to do or not to do something (Janmaimool and Denpaiboon, 2016). However, some studies consider it different in which motivation plays a role in describing intention (Heidari *et al.*, 2018; Fan *et al.*, 2019). Knowledge showed little correlation toward a willingness to the recycling of residents in 10 cities in China (Wang *et al.*, 2020a). Meanwhile, some other studies indicated that environmental and moral consideration factors, especially personal sense of responsibility (Mukama *et al.*, 2016; Heidari *et al.*, 2018; Liu *et al.*, 2019; Issock *et al.*, 2020; Wang *et al.*, 2020a), as well as past behaviour (Xu *et al.*, 2017) become the proper descriptors of intention to separation practice over other determinants. For example, a study conducted by Issock *et al.* (2020) aimed to analyse the influence of normative factors to waste separation behaviour of residents in Gauteng Province, South Africa, in 2019 showed that moral norms gave a more substantial and more lasting impact on intention. Thus, knowledge is not directly influential to intention, but it should be mediated by environmental awareness and personal moral norms. Elayan and Ebrawish (2017) found that recycling intention, combined with other determinant factors, influenced waste recycling implementation in Ayla Aviation Academy (AAA) in Jordan. Xu *et al.* (2017) and Wang *et al.* (2020b) also contended that Intention alone without being combined with other determinant factors might result in discrepancies between intention and behaviour. It implies that whenever one already intends to do waste management behaviour, it is still possible to do or not to do the behaviour if not supported by other determinant factors. Such a phenomenon is commonly called as an Intention-Action Gap (Hollingworth and Barker, 2017; Xu *et al.*, 2017; Wang *et al.*, 2020b). Some studies indicated that intention is correlated to external factors such as law enforcement (Song *et al.*, 2016; Ulhasanah and Goto, 2018), monetary factors (Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Alhassan *et al.*, 2020; Wang *et al.*, 2020b) and accessibility of facilities (Kattoua *et al.*, 2019; Zhang *et al.*, 2019; Alhassan *et al.*, 2020; Setiawan, 2020). However, it is worth noting that intrinsic factors are considered more impactful and more stable in driving the intended behaviour rather than external factors (Kattoua *et al.*, 2019; Issock *et al.*, 2020), while external factors tend to moderate and strengthen it (Wang *et al.*, 2020b). The disagreement between external effects and requirements to transform the intention would lead to Intention-Action Gap (Wang *et al.*, 2020b).

Personal moral norms

Personal moral norms are identified in the studies related to waste recycling behaviour (Heidari *et al.*, 2018), waste separation behaviour (Janmaimool and Denpaiboon, 2016; Yuan *et al.*, 2016; Loan *et al.*, 2017; Xu *et al.*, 2017, 2018; Heidari *et al.*, 2018; Zhang *et al.*, 2019; Issock *et al.*, 2020; Setiawan, 2020; Wang *et al.*, 2020b; Wang and Hao, 2020), waste reduction (Limon *et al.*, 2020), and waste management behaviour in general (Almasi *et al.*, 2019; Meng *et al.*, 2019; Issock *et al.*, 2020). There is no study discussing personal moral norms in waste reduction behaviour. Personal moral norms are defined as personal moral obligation or responsibility which enforce oneself to do waste management (Janmaimool and Denpaiboon, 2016; Issock *et al.*, 2020; Wang *et al.*, 2020b). It may also refer to the moral perception of waste management activities, which are good or bad, causing feeling guilty once they do or do not conduct the waste management behaviour (Loan *et al.*, 2017). Personal moral norm is sometimes called only personal norm (Loan *et al.*, 2017; Xu *et al.*, 2018) or moral norm (Issock *et al.*, 2020) or sometimes moral obligation (Xu *et al.*, 2017; Heidari *et al.*, 2018) as well. Personal moral norms are found to be the most potent descriptor of behaviour related to recycling (Heidari *et al.*, 2018; Limon *et al.*, 2020) and waste separation (Yuan *et al.*, 2016; Loan *et al.*, 2017; Zhang *et al.*, 2019; Issock *et al.*, 2020). Understanding toward separation obligation determines the acceptance of the activities (Liu *et al.*, 2019; Setiawan, 2020) even though it needs more effort to conduct it. Janmaimool and Denpaibon (2016) found that personal norms became a predisposition toward residents' behaviour in Thailand regarding waste separation. This factor becomes the indirect predictor of waste separation behaviour through attitude, as indicated by some studies (Loan *et al.*, 2017; Xu *et al.*, 2017; Heidari *et al.*, 2018; Liu *et al.*, 2019). Personal moral norms can directly affect waste separation intention and behaviour of residents in Hefei, Anhui Province, China (Wang *et al.*, 2020b) or indirectly through attitudes as found on residents' behaviour in Vietnam

(Loan *et al.*, 2017) and Hangzhou, China (Xu *et al.*, 2017). Wang *et al.* (2020b) argued that personal moral norms should be combined with awareness to correlate with waste separation attitude. Meanwhile, Meng *et al.* (2019) contended that primary intrinsic factors necessary to determine residents' behaviour are awareness, personal moral norms, and attitude to nurture intention. Wang *et al.* (2020b) involved knowledge and incentive combined with personal moral norms to improve residents' intention and behaviour toward waste separation in Anhui Province. However, according to an experiment conducted by Xu *et al.* (2018) in 2017 on Hangzhou residents, when comparing personal moral norms and incentive motivation, they found that personal moral norms were not significant in predicting waste separation behaviour. It is reasonable because the experiment study conducted by Xu *et al.* (2018) is in limited duration while changing personal moral norms takes time and needs intensive education. Hence, personal moral norms probably have not been nurtured yet when it was measured after the experiment. Personal moral norms should be combined with awareness and knowledge as other important intrinsic factors to establish attitude. Meanwhile, personal moral norms have a reciprocal relationship with social norms in a way that personal moral norms affect social norms (Xu *et al.*, 2018; Knickmeyer, 2019), while social norms are also affected by personal moral norms (Issock *et al.*, 2020; Xu *et al.*, 2018). In addition, personal moral norms can be influenced by external factors, such as authorities (Xu *et al.*, 2018; Wang and Hao, 2020). Thus, Wang and Hao (2020) suggested that China authorities evoke the residents' moral norms to nurture the intrinsic motivation of Chinese residents.

Perception of benefits

The perception of benefits was discussed in the studies related to waste separation behaviour (Li *et al.*, 2017; Heidari *et al.*, 2018; Sekito *et al.*, 2018; Fan *et al.*, 2019, Gyimah *et al.*, 2019), waste recycling behaviour (Elayan and Ibrawish, 2017) and waste management behaviour in general (Yukalang *et al.*, 2017). According to the study conducted by Gyimah *et al.* (2019) in 2016, residents in Ghana had a willingness to separate their waste if there is demand as well as a market for the valuable waste they got. Similarly, Yukalang *et al.* (2017) found that Thailand residents were unwilling to separate because they think waste had no value. Other studies found that perceived costs and benefits had the most decisive impact on the intention of residents to separate in China (Li *et al.*, 2017; Fan *et al.*, 2019; Ma *et al.*, 2020), in Vietnam (Nguyen and Watanabe, 2019) and university students in Iran (Heidari *et al.*, 2018) and various other countries. For example, the resident participation rate of separation activities in Nanjing, China, was significant and stable for more than 22 months since it first started (Li *et al.*, 2017). Every month, the residents could exchange their points to ten eggs or detergents, household-related services (e.g. sharpening knives, etc) (Li *et al.*, 2017). The points were gained from their separated waste collected by the officials. Another economic benefit is presented in Indonesian residents from Malang City who can earn 23.3 USD/ year from the waste bank, which was enough to buy school peripherals (Sekito *et al.*, 2018). Meanwhile, Thailand residents from Bangkok City can earn 15.6 USD from plastics waste and 14.2 USD from paper waste per year (Areeprasert *et al.*, 2018). In fact, Managua residents in Nicaragua gained 39% of their monthly income from waste, which was up to 185.4 USD per month (Hartmann, 2018). Consequently, 45% of Managua residents were actively involved in recycling activities as one of their income sources (Hartmann, 2018). On a medium scale, recycled organic waste that produced vermicompost worthed 80 USD/tonne in Uganda (Lim *et al.*, 2016), 106 USD/tonne in Bali, Indonesia and 180 USD/tonne in Srilanka, with 10% price increase estimation (Pandyaswargo *et al.*, 2014). For nationwide scale, the economic benefits could reach up to 11.71 million USD in Nigeria, which was equivalent to more than 16 thousand jobs/ year (Ayodele *et al.*, 2018). Economic benefits were proven to be effective to stimulate initial participation in Nanjing, China that eventually formed new habits about waste management (Li *et al.*, 2017). Besides economic benefits, perception of benefits can be in the form of environmental conservation (Ayob *et al.*, 2017; Elayan and Ibrawish, 2017), which are rooted in environmental awareness (Gyimah *et al.*, 2019; Nguyen and Watanabe, 2019; Limon *et al.*, 2020; Salem *et al.*, 2020). Environmental-based benefits were more significant in affecting waste separation behaviour of residents in Rural China (Ma *et al.*, 2020) and residents in Malaysia (Tiew *et al.*, 2015a), rather than economic-based benefits. The

insignificant effect of economic benefits could be due to a negligible amount of monetary benefits (Li *et al.*, 2017; Sekito *et al.*, 2018; Ma *et al.*, 2020). Therefore, Sekito *et al.* (2018) stated that economic value might be influential in the low economic residents since they are motivated to gaining additional income from the waste, as happened in Managua, Nicaragua (Hartmann, 2018). Sekito *et al.* (2018) also indicated that residents probably do not know the potential revenue from waste that makes them think that the waste has no value, as happened in Thailand (Yukalang *et al.*, 2017). Therefore, all related information about potential financial gains should be informed to the residents to ensure they have considered the revenue they might get (individually or communally) by practicing waste management (Sekito *et al.*, 2018). In addition, knowledge related to environmental-based benefits should also be informed to strengthen the effect. Hence, there is a balance between environmental-based reasons and the perception of waste management benefits to ensure they have sufficient motivation to participate. The combination of intensive information campaigns about environmental benefits and monetary incentives have been proven to significantly improve residents' waste segregation behaviour in India (Wadehra and Mishra, 2018). Elayan and Ebrawish (2017) suggested education such as awareness sessions or such a workshop to improve the understanding of the recycling benefits for academic students in Jordan.

Environmental efficacy

Wang and Hao (2020) mentioned the term environmental efficacy, which refers to confidence that individual efforts have the power to make environmental change. Even though some studies referred to this as self-efficacy (Janmaimool and Denpaiboon, 2016) or response efficacy (Fan *et al.*, 2019), the essence is more likely to refer to environmental efficacy. Environmental efficacy has proven to affect residents' waste separation behaviour in Shanghai, China (Fan *et al.*, 2019). In comparison, Loan *et al.* (2017) found that its effect was mediated by the Vietnamese residents' attitude, as indicated by their finding from the research conducted in urban areas in Thailand within 2015-2016. The absence of belief toward the environmental problems' solvability can be the barrier to waste management effectiveness (Yukalang *et al.*, 2017). It showed the importance of the resident's understanding of the waste management benefits, its significance in solving environmental problems caused by waste, and their roles toward waste problem-solving. Understanding of the benefits indicated the effect of perception of environmental benefits, implying its antecedent factor to environmental efficacy. Furthermore, Ramadan *et al.* (2016) found that residents in Bandung City, Indonesia, considered that the waste separation activities were ineffective, causing their reluctance in participation. Ramadan *et al.* (2016) indicated that the ineffective perception was caused by distrust to the local authorities responsible for the next step for the waste management process. Therefore, Fan *et al.* (2019) and Janmaimool and Denpaiboon (2016) suggested the authorities to educate the residents about waste separation benefits. Furthermore, Xu *et al.* (2018) implied the importance of understanding the residents' role in the waste management process to improve their environmental efficacy.

Subjective norms

Subjective Norms are the perception of an individual toward social norms. Subjective norms affected residents' intention to separate in Taiyuan City, China (Liu *et al.*, 2019) and residents in rural and semi-rural residents in Vietnam (Nguyen and Watanabe, 2019). But some studies indicated an insignificant effect to waste management behaviour, especially when compared to personal moral norms (Ayob *et al.*, 2017; Zhang *et al.*, 2019; Wang *et al.*, 2020b). However, Zhang *et al.* (2019) argued that subjective norms could be more significant in affecting intention to behaviour for the community where public perception toward their behaviour is essential (Xu *et al.*, 2017; Heidari *et al.*, 2018; Fan *et al.*, 2019; Nguyen and Watanabe, 2019; Issock *et al.*, 2020). As stated in the study by Issock *et al.* (2020), subjective norms do not include common behaviour conducted by society but more about the community's perceived expectation toward individuals. The subjective norms are applied when the expected behaviour is visible to other people to whom the perceptions are taken into individual considerations (Wang *et al.*, 2020b). It implied that subjective norms do not affect intention directly but moderating the intention to convert to action. According to Xu *et al.* (2017), subjective norms and PBC were less significant for residents in China

compared to habits. However, Stern *et al.* (1999) contended that habits might be disrupted when intervention such as educational activities improve individual dispositions that eventually form new behaviour. In this case, subjective norms can be the best way to develop new habits through social norms along with regulations, as indicated by some studies (Xu *et al.*, 2017; Liao *et al.*, 2018; Salem *et al.*, 2020;). Subjective norms can be moderated by regulation to affect Intention (Xu *et al.*, 2017). Therefore, Xu *et al.* (2017) suggested local governments in China adjust local regulation to the social norms to promote waste management behaviour toward households effectively.

Habits

Habits are defined as a series of learned acts which have been automatic and unconscious, based on specific triggers (Hollingworth and Barker, 2017). The studies about habitual factors of residents in developing countries are only found to be discussed in waste separation behaviour (Oduro-Kwarteng *et al.*, 2016; Ramadan *et al.*, 2016; Xu *et al.*, 2017; Liao *et al.*, 2018; Ulhasanah and Goto, 2018; Fan *et al.*, 2019). In comparison, habitual factors concerning recycling behaviour and reduction behaviour are only found in developed countries such as European Union (Minelgaitė and Liobikienė, 2019), Germany, and Israeli (Mintz *et al.*, 2019). Commonly developing countries are still dealing with separation problems in which residents' participation in waste separation is encouraged while recycling activities are mostly handled by the local authorities (Banerjee and Sarkhel, 2019). The study conducted by Fan *et al.* (2019), investigating the waste separation behaviour of households in Shanghai, China, in 2014, found that habits had a significant effect on Chinese residents' behaviour. The habits can be presented by repeating past behaviour, which positively influence willingness and separation behaviour (Liao *et al.*, 2018; Fan *et al.*, 2019). The effect of past behaviour is more significant to the residents in Hangzhou, China, compared to subjective norms and PBC (Xu *et al.*, 2017). The substantial effect of habits toward waste separation behaviour is also proven through the study conducted by Ramadan *et al.* (2016) and Ulhasanah and Goto (2018). They found that residents in Indonesia who were not familiar with waste separation tended to show a low willingness to do the long-term separation. Also, Oduro-Kwarteng *et al.* (2016) argued that unfamiliarity to waste separation activity, which tends to need full commitment to do, makes this activity often forgettable by Kumasi residents in Ghana, especially if separation activity is not their basic routine activities. Therefore, habits can intervene realization of intention to behaviour resulting Intention-Action Gaps phenomenon (Hollingworth and Barker, 2017). For instance, some people did not practice waste management due to laziness to change or just forgot doing it (Choon *et al.*, 2017; Trihadiningrum *et al.*, 2017). It indicated the role of habits as moderating factors toward intention to action. Xu *et al.* (2017) and Liao *et al.* (2018) suggested publication about separation performance in the public place to make public informed toward the existing behaviour. The information about the existing performance would encourage formation of social norms required to stimulate positive habits development toward waste management. In addition, habits can be enhanced by encouraging residents to practice it daily through habituation as an education method. Such a habituation process will create social norms pro to the new habit formation (Salem *et al.*, 2020). The habituation process has been successful in forming new habits of Chinese residents (Xu *et al.*, 2017; Liao *et al.*, 2018). To reduce the effect of negative habits toward waste management behaviour, Fan *et al.* (2019) encouraged strengthening the intention power to convert it to be behaviour.

Motivation

Motivation is defined as a driver (internal or external) of behaviour related to waste management. Motivation is found to be discussed in term of waste separation behaviour (Tiew *et al.*, 2015a; 2015b; Heidari *et al.*, 2018; Fan *et al.*, 2019; Limon *et al.*, 2020) and waste recycling behaviour (Heidari *et al.*, 2018; Lawrence *et al.*, 2020). Motivation is found to be a substantial determinant of the waste separation and recycling behaviour of residents in Malaysia (Tiew *et al.*, 2015a; 2015b), China (Fan *et al.*, 2019), Trinidad and Tobago (Lawrence *et al.*, 2020), and university students in Iran (Heidari *et al.*, 2018). The motivation can keep the resident behaviour longer-lasting (Tiew *et al.*, 2015a; Lawrence *et al.*, 2020). Intrinsic motivation can be nurtured based on the consideration of environmental conservation (Tiew *et al.*, 2015a; Fan *et al.*, 2019; Lawrence *et al.*, 2020)

and charity motivation as a result of personal moral obligations being nurtured by various values including religious beliefs (Abdelradi, 2018; Tiew *et al.*, 2015a; 2015b). Meanwhile, extrinsic motivation is more likely to be the result of their perception of economic benefits (Sekito *et al.*, 2018; Fan *et al.*, 2019). It implied that to develop the motivation to participate in the waste management, the residents should understand the benefits of the waste management activity for the environment and understand their role and moral obligation to keep the environment. In addition, residents should also be confident that their activity will affect the environment (Ramadan *et al.*, 2016) to ensure the transformation of the motivation to be behaviour. It indicated the importance of environmental efficacy to nurture intrinsic motivation. When intrinsic motivation has reached the maximum self-belief level, it may lower the external motivation as presented by residents in Trinidad and Tobago (Lawrence *et al.*, 2020). The internal motivation has made the recycling program in Trinidad and Tobago lasting more than three years (Lawrence *et al.*, 2020) and even lasting more than fifteen years in some religious communities in Malaysia such as Beautiful Gates, Tzu Chi Association, Surau Al-Husna, Batu Caves Temple (Mohamad *et al.*, 2012; Tiew *et al.*, 2015b). On the other hand, the absence of internal motivation may cause disinterest in participating that is considered the primary problem of waste management at the household level (Limon *et al.*, 2020).

Trust to local authorities

The studies related to trust to local authorities are found only on waste separation behaviour of residents in Vietnam (Loan *et al.*, 2017; Nguyen and Watanabe, 2019), Indonesia (Trihadiningrum *et al.*, 2017), Palestine (Salem *et al.*, 2020) and China (Wang and Hao, 2020) because waste separation activity in developing countries is typically integrated with the municipal waste management handled by the local authorities. Waste separation is the first step of the whole waste management process, conducted at the household level. The separated waste is processed further by the authorities (communal level or city level). Due to such a collaboration, trust to local authorities matters to ensure residents' participation in the waste separation process. The trust became a positive and significant driving force toward the waste separation behaviour of residents in Vietnam (Loan *et al.*, 2017; Nguyen and Watanabe, 2019) and in China (Wang and Hao, 2020). Meanwhile, Salem *et al.* (2020) reported that distrust toward authority performance on the collection step becomes a major obstacle to waste separation practice in Gaza Strip in Palestine. Similarly, Trihadiningrum *et al.* (2017) reported that when local authorities in Surabaya City, Indonesia, showed an inability in waste separation practice at the communal level in Surabaya City through its officers' performance, it affected the resident behaviour toward waste separation. Therefore, Loan *et al.* (2017) indicated that strong leadership would strengthen trust. Therefore, sharing knowledge related to the authorities' waste management performance will be effective in enhancing the trust to the authorities. However, according to the study conducted by (Wang and Hao, 2020) aimed at evaluating the role of central and local government to individual waste separation behaviour in China using China ational dataset from 2013, it was found that when the central authorities were trusted to handle the whole process of the waste management, the residents tended to shift their responsibility to the authorities. It implied that residents would not separate because they trust the government to separate the waste. Thus, improving their understanding of household responsibility on waste separation and understanding toward the mutual partnership between residents-authorities is required.

Life style

The lifestyle factor seemed less interesting to be analysed when discussing about determinant factors of waste management behaviour. Lifestyle is taken into consideration based on the study conducted by Choon *et al.* (2017), focusing on the waste reduction behaviour among Malaysian residents, specifically in the Klang Valley. Choon *et al.* (2017) identified three primary reasons for individuals not using a recycle bag: "forget", "laziness to change," and "have no time doing that". According to the three reasons mentioned, it seemed that Lifestyle could be a representation of Habits that are highly correlated to past behaviour and PBC (Oduro-Kwarteng *et al.*, 2016; Choon *et al.*, 2017; Trihadiningrum *et al.*, 2017). Due to its similarity, lifestyle will not be discussed further in this study because lifestyle factor is embedded in habits factors.

Extrinsic factors affecting waste management behaviour

There are 5 extrinsic factors identified from 57 studies which are directly affecting the intrinsic factors. The identified extrinsic factors are education, economic factor, supporting facilities, regulation related to waste management, and social norms. The number of papers mentioning each factor is presented in Table 5.

Waste management education

Education toward waste management is one of the most dominant factors affecting intrinsic factors since it is the most highly mentioned factor in 29 papers. Effective education is often considered as a robust solution to nurture intrinsic factors effectively to improve waste management behaviour (Idamah, 2015; Nnaji, 2015; Oduro-Kwarteng *et al.*, 2016; Al-Khateeb *et al.*, 2017; Choon *et al.*, 2017; Padilla and Trujillo 2018; Wadehra and Mishra, 2018; Kattoua *et al.*, 2019; Lawrence *et al.*, 2020; Nmere *et al.*, 2020). Even though extrinsic factors are available such as infrastructure, there is no assurance that the residents want to participate if they have no proper environmental awareness and technical knowledge toward the activity (Kattoua *et al.*, 2019). The educational system is supposed not only applied to the formal system (such as school-based or college-based education), which is commonly intended for youth (Singer *et al.*, 2019). The local government should provide an educational system specifically designed for adults as well in the concept of resident-based education (Singer et al., 2019; So *et al.*, 2019). The waste management education will improve specific residents' knowledge to nurture various intrinsic factors needed to improve participation (Navykarn and Muneenam, 2015; Liu *et al.*, 2019). Moreover, some studies found that educational contents being shared in resident-based education play a vital role in determining which intrinsic factors being nurtured (Janmaimool and Denpaiboon, 2016). Different contents emphasized in the education activities may affect various intrinsic factors (Song *et al.*, 2016; Al-Naggar *et al.*, 2019; Fan *et al.*, 2019; Wang *et al.*, 2020b). Meanwhile, it needs intrinsic factors to effectively improve waste management behaviour (Navykarn and Muneenam, 2015). Thus, it is crucial to determine what contents should be shared in the resident-based education to ensure its effectiveness in encouraging their waste management participation. After a more thorough investigation to identify the educational contents required, 38 papers mentioned what knowledge they suggested or already applied in their education system to improve resident participation in waste management. The content analysis of all the selected papers is mapped using the NVIVO R1 tool and presented in Table 6. The educational contents shown in Table 6 should be disseminated to the residents through resident-based education. The education is supposed to be conceived in a durable education program to ensure its effectiveness in conveying the learning contents (Oduro-Kwarteng *et al.*, 2016; Loan *et al.*, 2017; Knickmeyer, 2019). A long-term education program also allows continuous learning leading to accumulative improvement on intrinsic factors and waste management performance (Yeh *et al.*, 2016). Knowledge sharing activities can use various techniques and approaches involving multiple media and applying communication strategies adjusted to the residents' characteristics (Mamady, 2016; Knickmeyer, 2019). The educational setting might allow intensive interaction such as face-to-face interaction for better knowledge internalization (Knickmeyer, 2019), involving internet (Padilla and Trujillo, 2018) and learning-by-doing to encourage changing behaviour and improve waste management performance (yeh *et al.*, 2016). The Learning-by-

Table 5: Identified extrinsic factors affecting waste management behaviour

No	Intrinsic factors	Waste reduction behaviour	Waste separation behaviour	Waste recycle behaviour	Waste management behaviour	Number of papers
1	Waste management Education		√	√	√	29
2	Economic factor	√	√	√	√	27
3	Facilities	√	√	√	√	27
4	Regulation	√	√	√	√	20
5	Social norms		√	√	√	16

Table 6: Educational contents to nurture intrinsic factors

Type of contents	Terms	Intrinsic factors nurtured	References
1. Skills on waste management practice	• Method of waste storage, waste separation, waste reuse, waste recycle, waste disposal • Simple tips for waste management practice • Personal waste management • Tips on material use efficiency	Technical knowledge, PBC	Navykarn and Muneenam (2015); Tiew *et al.* (2015b); Janmaimool and Denpaiboon (2016); Oduro-Kwarteng *et al.* (2016); Song *et al.* (2016); Astane and Hajilo (2017); Choon *et al.* (2017); Elayan and Ebrawish (2017); Xiao *et al.* (2017); Fredrick *et al.* (2018); Sekito *et al.* (2018); Ulhasanah and Goto (2018); Yeung and Chung (2018); Al-Naggar *et al.* (2019); Gyimah *et al.* (2019); Kattou *et al.* (2019); Singer *et al.* (2019); Salem *et al.* (2020); Wang *et al.* (2020b); Wang and Hao (2020)
2. Bad impacts of waste	• Environmental problems (e.g. pollutions, damages) • Disasters (e.g. flood) • Health problems • Landfill problems	Environmental awareness	Navykarn and Muneenam (2015); Song *et al.* (2016); Janmaimool and Denpaiboon (2016); Mamady (2016); Mukama *et al.* (2016); Trihadiningrum *et al.* (2017); Yukalang *et al.* (2017); Fredrick *et al.* (2018); Yeung and Chung (2018); Al-Naggar, *et al.* (2019); Fan *et al.* (2019); Gyimah *et al.* (2019); Kattou *et al.* (2019); Lawrence *et al.* (2020); Limon *et al.* (2020); Wang *et al.* (2020b)
3. Importance of proper waste management practice	• Consequence of improper waste management to environment • Contribution to waste reduction • Importance of waste reduction, waste separation, waste recycling, waste disposal,	Attitude, environmental awareness, PBC	Nnaji (2015); Yuan *et al.* (2016); Choon *et al.* (2017); Elayan and Ebrawish (2017); Loan *et al.* (2017); Ma *et al.* (2018); Kattou *et al.* (2019); Sujata *et al.* (2019); Limon *et al.* (2020); Salem *et al.* (2020); Wang and Hao (2020)
4. Individual and social roles of waste problems using environmental and religious value approach	• Impact of human activities toward environment • Responsibility to the environment and handling waste • Significance of individual and community participation to waste management for solution to environmental problems	Understanding on individual and personal responsibility, personal moral norms	Tiew *et al.* (2015a); Janmaimool and Denpaiboon (2016); Mukama *et al.* (2016); Yuan *et al.* (2016); Almasi *et al.* (2019); Al-Naggar, *et al.* (2019); Lawrence *et al.* (2020); Wang and Hao (2020)
5. Information about the existing performance of waste management	• Operational cost of handling waste • Feedback on the recycling/separation practice • Comparison between recent recycling/separation behaviour and predefined standard	Knowledge about WM performance, self-efficacy, habits, trust to authorities	Tiew *et al.* (2015b); Yuan *et al.* (2016); Liao *et al.* (2018); Yeung and Chung (2018); Kattou *et al.* (2019); Setiawan *et al.* (2019)
6. Environmental Issues	• Environmental news • Environmental phenomena • Environmental protection & resource conservation	Environmental awareness	Idamah (2015); Janmaimool and Denpaiboon (2016); Song *et al.* (2016); Choon *et al.* (2017); Elayan and Ebrawish (2017); Fan *et al.* (2019)
7. Information toward extrinsic factors (regulation, social norms)	• Informing the existence of social norms toward 3R • Informing about available recycling facilities • Informing about regulation toward 3R	Knowledge about regulation and social norms, attitude, subjective norms	Janmaimool and Denpaiboon (2016); Choon *et al.* (2017); Liao *et al.* (2018); Yeung and Chung (2018)
8. Economic value of waste and its marketing opportunity	• Profit from selling recycle waste • Tips on marketing of recyclable waste • Possible revenue from selling valuable waste	Perception of benefits	Yukalang *et al.* (2017); Fredrick *et al.* (2018); Sekito *et al.* (2018); Kattou *et al.* (2019)

doing method can be implemented through social norms and regulation enforcement that allow the residents' habituation process.

Economic factors

There are 27 studies found discussing economic factors related to waste management behaviour. Economic factors refer to any economic or financial system involved to encourage waste management participation. The economic factors are presented in either reward or punishment provided by the local government. Reward concept can be through discounted taxes (Gyimah *et al.*, 2019; Kattoua *et al.*, 2019; Meng *et al.*, 2019), daily-good exchanges (Li *et al.*, 2017), financial incentives (Mukama *et al.*, 2016; Ng and Wang, 2017; Xiao *et al.*, 2017 Heidari *et al.*, 2018; Liao *et al.*, 2018; Ma *et al.*, 2018; Wadehra and Mishra, 2018; Fan *et al.*, 2019; Gyimah *et al.*, 2019; Wichai-utcha and Chavalparit, 2019; Salem *et al.*, 2020; Ma *et al.*, 2020; Wang *et al.*, 2020b), or a market system that enables residents to sell their recyclable waste (Tiew *et al.*, 2015a; Elayan and Ibrawish, 2017; Trihadiningrum *et al.*, 2017; Hartmann, 2018; Sekito *et al.*, 2018; Kattoua *et al.*, 2019; Meng *et al.*, 2019; Almasi *et al.*, 2019; Alhassan *et al.*, 2020). The punishment concept can be in the forms of a waste charge (Song *et al.*, 2016; Addo *et al.*, 2017; Xiao *et al.*, 2017; Yukalang *et al.*, 2017; Meng *et al.*, 2018), such as Pay As You Throw (PAYT) concept (Oduro-Kwarteng *et al.*, 2016; Addo *et al.*, 2017; Xiao *et al.*, 2017). Wang *et al.* (2020b) found that financial incentives can lower gaps between intention-behaviour on residents in Hefei, Province of Anhui, China. Similarly, Li *et al.* (2017) found that the daily-goods exchange concept implemented in Nanjing City, China, was also proven successful in encouraging the residents' stable participation toward waste separation programs. To encourage recyclable inorganic waste, some countries such as Indonesia (Trihadiningrum *et al.*, 2017; Sekito *et al.*, 2018), Malaysia (Tiew *et al.*, 2015a), and Nicaragua (Hartmann, 2018) provided a market system that enables the residents to sell their recyclable inorganic waste. By informing the potential revenue from the separated waste, the residents will know the economic benefits and are expected to be more interested in participating actively in the waste management program (Sekito *et al.*, 2018). However, financial rewards were commonly significant in affecting the motivation of low-income residents to participate in waste separation (Addo *et al.*, 2017; Ng and Wang, 2017; Hartmann, 2018; Sekito *et al.*, 2018; Almasi *et al.*, 2019; Kattoua *et al.*, 2019; Alhassan *et al.*, 2020), and were not significant for high-income residents (Meng *et al.*, 2019). High-income people tend to think that the revenue is meagre and not worth the efforts (Yukalang *et al.*, 2017; Sekito *et al.*, 2018). Therefore, they felt reluctant to participate (Yukalang *et al.*, 2017). However, even though financial rewards gave less motivation to participate (Tiew *et al.*, 2015a), the charity motivation played a more significant role that keeps Malaysian residents willing to participate in the recycling activities. Another factor affecting waste management participation concerning economic factors is the cost burden, as found on rural residents in China (Ma *et al.*, 2020) and Malaysia residents (Tiew *et al.*, 2015a). With the same logic, punishment for absence in participation, leads to additional cost and might be powerful to encourage residents to participate. The punishment concept allows local government to charge residents for their waste through the PAYT mechanism. Even though the PAYT concept implementation had an insignificant impact in some areas, such as in Xiamen City, China (Xiao *et al.*, 2017), but it was effective for some other areas such as Macau (Song *et al.*, 2016) and Suzhou, China (Meng *et al.*, 2018). The reasons can be because of the benefits received such as improvement on services, or because of expense avoidance. PAYT concept may be more suitable for high-incomes cities where the residents want to pay more for better waste management service (Song *et al.*, 2016). The cities already have a good system for waste management and policy-related enforcement. Thus, PAYT will not give misleading messages, such as encouraging residents to dispose their waste improperly due to expense avoidance. For better implementation, Oduro-Kwarteng *et al.* (2016) suggested implementing a drop-off concept in Kumasi Metropolis, Ghana, to allow residents to drop-off their recyclable waste without charging them. The bill will be reduced if the residents want to bring their waste themselves. Nevertheless, Xiao *et al.* (2017) stated that the charging concept is a less preferred option for Xiamen residents even though it has been widely used due to its feasibility to reduce waste for other countries.

Supporting facilities

There were 27 studies discussing about supporting facilities for waste management to

improve participation (Song *et al.*, 2016; Akhtar *et al.*, 2017; Hammami *et al.*, 2017; Trihadiningrum *et al.*, 2017; Fredrick *et al.*, 2018; Liao *et al.*, 2018; Almasi *et al.*, 2019; Fan *et al.*, 2019; Kattoua *et al.*, 2019; Meng *et al.*, 2019; Zhang *et al.*, 2019; Alhassan *et al.*, 2020; Lawrence *et al.*, 2020; Setiawan, 2020; Wang *et al.*, 2020b). Some factors to consider related to supporting facilities include the accessibility of the collecting point facilities from the residentials (Tiew *et al.*, 2015a; Nnaji, 2015; Addo *et al.*, 2017; Choon *et al.*, 2017; Yukalang *et al.*, 2017; Gyimah *et al.*, 2019; Meng *et al.*, 2019; Ma *et al.*, 2020; Alhassan *et al.*, 2020), the capacity and sufficiency of the facilities (Nnaji, 2015; Akhtar *et al.*, 2017; Choon *et al.*, 2017; Heidari *et al.*, 2018; Kattoua *et al.*, 2019), the variability for various types of waste (Lawrence *et al.*, 2020), and the arrangement of the storage and its appearance (Oduro-Kwarteng *et al.*, 2016; Choon *et al.*, 2017). For the area where space available is limited to place the facilities near to the residents, it is recommended to implement a kerbside waste collection system, a service given to the households to collect and dispose of the separated waste to the collecting point (Oduro-Kwarteng *et al.*, 2016). In this case, the waste charging system will affect its success to encourage participation. Liu *et al.* (2019) indicated that supporting facilities affected the PBC of residents in Taiyuan City, China. Wichai-utcha and Chavalparit (2019) argued that when supporting factors were combined with financial incentives and implementation of regulations, supporting facilities improved waste management participation of residents in Thailand. However, it is found a negative moderating effect of facilities' availability to the participation rate in Shanghai due to an absence of supervision process (Fan *et al.*, 2019). Moreover, Zhang *et al.* (2019) stated that supporting facilities factors were not significant in moderating the Intention-Behaviour Gap of waste separation behaviour in Taishan District, Shandong Province, China. Instead, facilities can directly affect the residents' waste separation behaviour (Zhang *et al.*, 2019). In this case, Zhang *et al.* (2019) argued that people could separate their waste once they find supporting facilities around them, supporting with knowledge toward government support. In this regard, Kattoua *et al.* (2019) explained that there is no insurance that residents will participate if they have no intrinsic factors to support the behaviour. Lawrence *et al.* (2020) contended that when the intrinsic driver is strong (e.g. environmental-based reasons), there is no need for the external driver to motivate the residents. In this way, external factors have functioned as the moderator of intention to real action as what was found in Trinidad & Tobago. Therefore, encouraging residents from improving intrinsic factors is highly recommended, while the external supports are combined in strengthening the effects, especially for the residents who still have low internal drivers.

Regulation related to waste management

The implementation of regulation in waste management has been discussed in 20 studies. Regulation can be related to official recycling program (Kattoua *et al.*, 2019) along with the organizational plan about waste management procedure (Almasi *et al.*, 2019), including regulation about waste separation process (Gyimah *et al.*, 2019), recycling and waste reduction process (Oduro-Kwarteng *et al.*, 2016). Xiao *et al.* (2017) found that regulation became the least favourable choice to improve residents' participation in Xiamen City, China, compared with knowledge and social norms. Regulation tended to lack application and control and was considered only a conditional instrument (Xiao *et al.*, 2017). Ma *et al.* (2018) reported that regulation was significant in affecting the pro-environmental attitude of residents in Guangxi Zhuang, China, according to their study conducted in 2014. Meanwhile, two studies found that regulations were not statistically significant in encouraging the residents' waste management behaviour in Suzhou, China (Meng *et al.*, 2019) and South Africa (Issock *et al.*, 2020). Meng *et al.* (2019) explained that because the regulation implemented in Suzhou, China was limited to the incentive system and instruction without mandatory encouragement. Moreover, Meng *et al.* (2019) indicated that voluntary motivation was less recommended due to low power to enforce participation, which was agreed by other studies (Ma *et al.*, 2018; Putri *et al.*, 2018; Wichai-utcha and Chavalparit, 2019; Wang *et al.*, 2020a). On the other hand, Issock *et al.* (2020) argued that the insignificancy effect of regulation toward residents' waste management behaviour in South Africa because the residents did not know yet about the regulation. Also, Wang and Hao (2020) argued that the contrary effects of government intervention

(regulation) found in various studies were due to the different expectations between the government and the social norms. It indicated a mutual correlation between regulation and social norms, which are expected to be in line. Thus, it can be concluded three things: First, the regulation should encourage mandatory participation to establish social norms (Liao *et al.*, 2018; Wang *et al.*, 2020a; Issock *et al.*, 2020). Second, there should be accordance between the regulation and the social norms. In this case, explicit instruction and guidelines to create a more supportive environment are also encouraged (Oduro-Kwarteng *et al.*, 2016; Yukalang *et al.*, 2017; Salem *et al.*, 2020) to build new habits of the community that is pro to waste management. Third, it is essential to disseminate regulation to ensure that the residents have sufficient knowledge about it (Sujata *et al.*, 2019). Sufficient knowledge toward the regulation can be relied on for the participation initial stage (Ma *et al.*, 2018). It implies that education should involve regulation dissemination and socialization to enable the residents to understand their expected roles. However, as indicated by Sujata *et al.* (2019) and Wichai-utcha and Chavalparit (2019), it is worth noting that educating residents merely on regulation dissemination is less effective in improving participation. Support from other extrinsic factors is required, such as economic factors and supporting facilities (Yeung and Chung, 2018; Wichai-utcha and Chavalparit, 2019; Salem *et al.*, 2020). Furthermore, based on the study's finding by (Xu *et al.*, 2017), it is implied that the effectiveness of regulation can moderate subjective norms to intention while also translating PBC to behaviour.

Social norms

There were 16 studies related to social norms, with diverse terms such as local trends in the area (Choon *et al.*, 2017), public praise (Liao *et al.*, 2018), cultural norms (Pasaribu *et al.*, 2020), and community norms (Janmaimool and Denpaiboon, 2016). Social norms also include social pressure from families (Yuan *et al.*, 2016; Loan *et al.*, 2017; Xiao *et al.*, 2017), neighbours (Yuan *et al.*, 2016; Xiao *et al.*, 2017; Meng *et al.*, 2019), friends or even local leaders (Trihadiningrum *et al.*, 2017) which enable to give impact to individual behaviour toward waste management. The social norms are converted to subjective norms on individuals, based on their perception of the norms. Issock *et al.* (2020) differentiated between descriptive norms, norms coming from other people's behaviour, and injunctive norms, norms coming from other people's expectations. They indicated that injunctive norms are more impactful than descriptive norms (Issock *et al.*, 2020). It could be because the motivation to do the action is more likely to be face-saving than care for the environment (Liao *et al.*, 2018). According to many previous studies, social norms showed a significant effect on the intention to do waste management behaviour directly (Choon *et al.*, 2017; Wadehra and Mishra, 2018; Meng *et al.*, 2019; Issock *et al.*, 2020; Pasaribu *et al.*, 2020) or through subjective norms (Trihadiningrum *et al.*, 2017; Xiao *et al.*, 2017; Xu *et al.*, 2017; Liao *et al.*, 2018; Ulhasanah and Goto, 2018; Sujata *et al.*, 2019). However, Sujata *et al.* (2019) contended that even though social norms significantly affect intention, the effect is small. It is because social norms are commonly powerful for behaviour, which are seen by other people, while the intention is invisible (Wang *et al.*, 2020b). Furthermore, Zhang *et al.* (2019) implied that intention is more likely to be affected by personal moral norms rather than subjective norms (Zhang *et al.*, 2019; Issock *et al.*, 2020; Wang *et al.*, 2020b). While it is found the contrary result of whether social norms are influential in both urban areas (Choon *et al.*, 2017) and the rural areas (Janmaimool and Denpaiboon, 2016), it seems that the effect is relied on the cultural background, in which face-saving is prevalent in the areas (Liao *et al.*, 2018). Likewise, Janmaimool and Denpaiboon (2016) and Meng *et al.* (2019) argued that social norms are strongly required by the community where public expectation has a strong effect on encouraging resident behaviour. The community may influence subjective norms from the family members, friends, or neighbour's behaviour (Loan *et al.*, 2017) once the individual thinks that their behaviour matches the community norms (Xiao *et al.*, 2017). In the case where social norms affect individual behaviour, Xiao *et al.* (2017) contended that the influence is stronger than the effect of regulations. It should be noted that the effect is also depending on how far the individual understand the norms (Janmaimool and Denpaiboon, 2016). Thus, residents' understanding toward social norms should be improved through massive promotion (Janmaimool and Denpaiboon, 2016; Meng *et al.*, 2019), especially in the area where face-saving or public expectation

plays a vital role in their culture. Eventually, social norms should be included in the educational content to ensure the residents understand it.

Proposed model

Based on a thorough analysis of waste management behaviour conducted previously, the proposed model is built based on two primary areas: extrinsic and intrinsic factors. The extrinsic factors refer to any intervention factors outside the personal domain that could affect personal behaviour. In contrast, intrinsic factors are determinant factors inside the personal domain that involves the behaviour realization process (Stern, 1999). In the area of intrinsic factors, there are three primary domains: knowledge, emotional and behavioural level, which are inspired by the behavioural theory concepts indicating the process of how an individual can finally do a certain behaviour (Lickona, 1991; Stern, 1999; Ajzen, 2005). Some interventions can be involved to improve personal behaviour. Previous studies related to waste management behaviour identified that extrinsic factors were significantly affecting the improvement of waste management behaviour, including education, economic factors, supporting facilities, regulations, and social norms. The education is to share facts, values, and information as the education contents (Stern, 1999). Relevant contents being shared in the educational system are vital to ensure the relevance of knowledge received by the households, which are significantly influential in improving certain intrinsic factors (Janmaimool and Denpaiboon, 2016; Hammami *et al.*, 2017; Xu *et al.*, 2017; Yeung and Chung, 2018). It is identified eight primary contents required to be educated to the households, as shown in Table 6. The contents should address the relevant issues to make them effective (Knickmeyer, 2019). The education will improve technical knowledge (including skills on doing the waste management procedure), knowledge about recent waste management performance in the given area, the perceived environmental and economic benefits from waste management, environmental awareness, knowledge about relevant social norms and regulations, and also understanding toward residents' responsibility to waste management. The direct effect of knowledge acquired by the residents improves key intrinsic factors on the emotional level (Hammami *et al.*, 2017; Xu *et al.*, 2017; Wang *et al.*, 2020a), such as residents' trust toward authorities, environmental efficacy, motivation, personal moral norms, and subjective norms. The perceived norms from the community have reciprocal effects on personal moral norms. On the other hand, the combination of personal moral norms and motivation will be powerful to improve attitude toward waste management (Mukama *et al.*, 2016). The motivation should be nurtured through the combination of perception of benefits and environmental awareness (Wadehra and Mishra, 2018) while also influenced by environmental efficacy (Ramadan *et al.*, 2016) and personal moral norms, as a result of understanding toward residents' responsibility toward the environment (Abdelradi, 2018; Tiew *et al.*, 2015a). The environmental efficacy itself should be built from the perception of benefits, environmental awareness, understanding of responsibility, and trust to the authorities, which is the effect of knowledge toward recent waste management performance (Wang and Hao, 2020; Xu *et al.*, 2018). The combination of technical knowledge, support of facilities, and environmental efficacy will improve PBC (Yuan *et al.*, 2016; Xu *et al.*, 2018; Liu *et al.*., 2019). When PBC is combined with motivation and personal norms, it will affect the attitude toward waste management (Yuan *et al.*, 2016; Yukalang *et al.*, 2017; Liu *et al.*, 2019). The given attitude will eventually cause the intention to do waste management (Addo *et al.*, 2017; Xu *et al.*, 2017; Almasi *et al.*, 2019). The PBC and personal moral norms separately can also cause intention to do waste management, but the intention will be weak if there is no existing positive attitude (Mukama *et al.*, 2016; Heidari *et al.*, 2018; Liu *et al.*, 2019; Issock *et al.*, 2020; Wang *et al.*, 2020a). When it comes to converting intention to behaviour, economic factors, subjective norms, and the existing habits play as moderating factors that may loosen or strengthen the realization (Kattoua *et al.*, 2019; Issock *et al.*, 2020; Wang *et al.*, 2020b). If the intention is weak due to a lack of support from antecedents and extrinsic factors, the existing habits will determine the behaviour realization (Wang *et al.*, 2020b). Therefore, the key contents in the educational system should meet the requirements, and those key contents should be able to nurture the determinant factors from the intrinsic domain to strengthen the intention. Further, the intention which comes from intrinsic factors will be converted to more sustainable behaviour (Kattoua

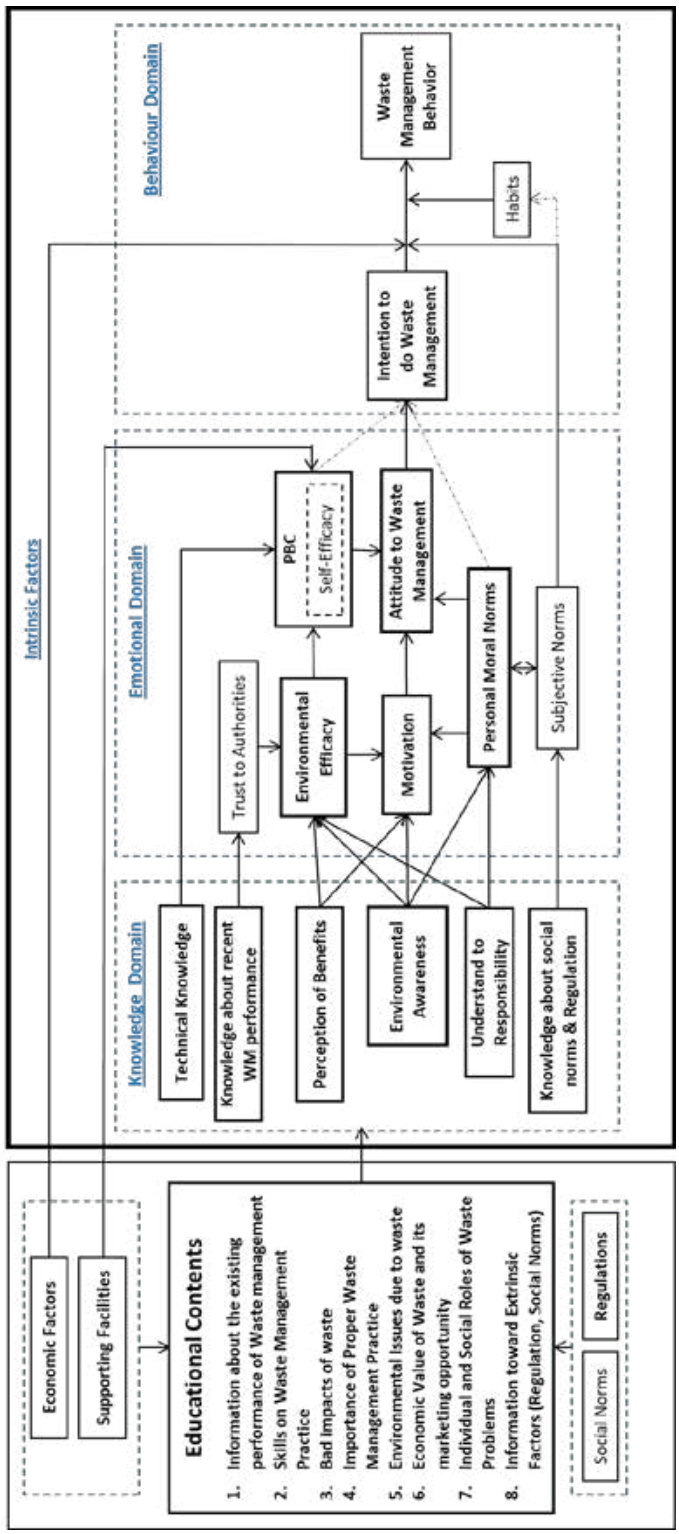

Fig. 2: The relationship among intrinsic and extrinsic factors affecting waste management behaviour

et al., 2019; Zhang *et al.*, 2019; Issock *et al.*, 2020), especially when extrinsic factors and habits are fully supporting. As a result, the residents willingly participate in waste management actively. The relationship among all identified determinant factors is presented in Fig 2. The bold-written variables in the figure show the emphasis of its urgency based on the literature's support and the cruciality of the existence in the model.

Model formulation

According to Fig. 2, It is seen that among external factors, educational contents become the crucial factors that should be existed to ensure improved behaviour on waste management through intrinsic factors improvement. Extrinsic factors are required as moderating factors that are intended to strengthen their realization. Subjective norms come from social norms, which are only significant for the community that considers social perception toward them is important (Xu *et al.*, 2017; Heidari *et al.*, 2018; Fan *et al.*, 2019; Issock *et al.*, 2020). Meanwhile, there is a reciprocal correlation between personal norms and subjective norms. Thus, personal moral norms can be representative for the subjective norms. Therefore, subjective norm factor is omitted in the model. Furthermore, social norms can be combined with regulation to lead to new habits establishment (Xu *et al.*, 2017; Li *et al.*, 2017; Liao *et al.*, 2018; Salem *et al.*, 2020). Such a habituation approach becomes an effective educational method to make the residents familiar with the behaviour (Lickona, 1991) because it allows learning by doing (Yeh *et al.*, 2016). Once the behaviour becomes habits, it reduces the dependence on external factors such as economic factors (Li *et al.*, 2017). The habituation will strengthen the behaviour improvement by making it mandatory (Liao *et al.*, 2018; Wang *et al.*, 2020b; Issock *et al.*, 2020). The mandatory regulation is disseminated through social norms and becomes one of the educational contents to ensure that residents' proper knowledge of the mandatory status. Therefore, it will encourage the initial stage of participation (Li *et al.*, 2017; Ma *et al.*, 2018; Sujata *et al.*, 2019). In terms of emotional level, according to Ajzen (2005), attitude consists of three domains: cognitive, affective, and conative. The cognitive domain is represented through personal beliefs toward behaviour given through environmental efficacy (Ayob *et al.*, 2017) and personal moral norms (Almasi *et al.*, 2019). The term attitude itself often represents the affective domain, which refers to either like or dislike position (Choon *et al.*, 2017; Heidari *et al.*, 2018; Alhassan *et al.*, 2020). Meanwhile, intention is the conative domain of Attitude (Ajzen, 2005). Therefore, Intention is unified with the attitude component. However, environmental efficacy and personal moral norms should be independent because their existence should show the causal effect of the knowledge domain and other antecedent factors. For environmental efficacy, one of the affecting components is trust to authorities by strengthening the belief of the behaviour's effectiveness to solve environmental problems. However, other affecting factors are understanding the responsibility toward environmental problems both personally and socially, including the authority's responsibility (Mukama *et al.*, 2016; Almasi *et al.*, 2019; Wang *et al.*, 2020b). Thus, the trust of Authorities can be eliminated from the model. By eliminating the factors which are not necessarily required to appear and highlighting the key factors that should be existing as the descriptors of the antecedent factors, the modified model is presented in Fig. 3. The proposed model presented in Fig. 3 offered a more comprehensive view of all key intrinsic-extrinsic factors' relationship and portrayed the intrinsic factors on knowledge level and emotional level, improving the existing models offered by most previous studies. The proposed model also emphasized the importance of knowledge and identified key educational contents as the preceding factors to properly nurture intrinsic factors on an emotional level, which are unnoticed by most of previous studies. The proper improvement of intrinsic factors on the emotional level plays a vital role in nurturing a stable attitude which leads to sustainable changing behaviour. Taking more attention toward all crucial intrinsic-extrinsic factors is expected to give more effective ways to improve residents' behaviour that lead to sustainable participation on waste management. However, the proposed model is not a one-fits-all applicable to any situation because the dominant extrinsic and intrinsic factors may differ from one city to another city. The approaches to share the eight key educational contents should be adjusted to the relevant context to the cities (Knickmeyer, 2019). For instance, the cities experiencing flood disasters can emphasize

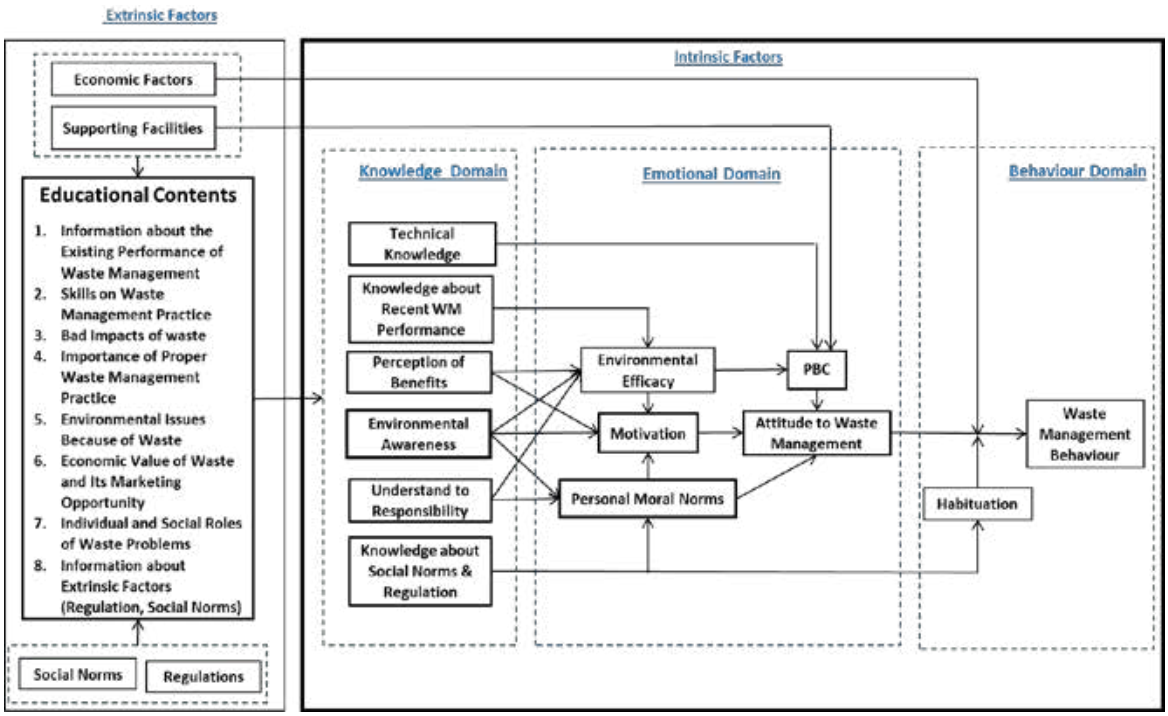

Fig. 3: The proposed model

sharing information about the correlation between their residents' bad behaviour toward waste and the disaster and then offer a solution to solve the flood problems (Lawrence *et al.*, 2020). On the other hand, the cities dominated by low-income residents may emphasize economic benefits by showing the real benefits they can get from the waste. While social norms are not significant in many areas, some other cities with face-saving culture may place social norms as one of the key extrinsic factors. Whilst, communities with religious culture may focus on disseminating religious-based values related to individual and social obligations and environmental conservation, in addition to the other common contents, to encourage changing behaviour. Regardless of the emphasis and approach implemented, the focus should nurture the key intrinsic factors on both knowledge and emotional level to get strong intention. While the extrinsic factors give full support on the intention realization.

RECOMMENDATION

This study has two primary implications for theory and practice. First, the literature review offers different insights in analyzing determinant factors by figuring out causal relationships between extrinsic and intrinsic factors. The proposed model showed the importance of knowledge and emotional domain within intrinsic factors to get sustainable changing behaviour toward waste management. Second, the identification of educational contents must be shared in the resident-based education to nurture key intrinsic factors affecting waste management behaviour, which rarely get attention in the previous studies. Further research may focus on testing the proposed model in the waste management system in specific areas in developing countries. This study is beneficial, especially for local governments or policymakers to refine their programs intended for resident participation improvement on the waste management system.

CONCLUSION

According to the comprehensive literature review conducted, five extrinsic factors play vital roles in cultivating intrinsic factors that significantly affect waste management behaviour. Among the extrinsic factors identified, education is essential

to boost intrinsic factors on an emotional level by improving residents' knowledge of key contents. The knowledge acquisition influences the intrinsic factors improvement on emotional level, leading the expected behaviour. The changing behaviour becomes the indication that the residents willingly participate in waste management. Improving waste management participation by nurturing key intrinsic factors, supported by external factors and habituation, is essential to keep the participation long-lasting. With full support from the antecedent factors, waste management behaviour can be sustainable, which eventually increases the participation rate significantly. However, the impact degree of antecedent factors, extrinsic and intrinsic, can be contextually different from one city to another. Therefore, educational contents' relevance to the residents' environmental problems is highly encouraged to nurture the critical intrinsic factors. The familiarity of educational materials to the residents' waste problems will make the knowledge more impactful. The educational contents are delivered through resident-based education using various techniques and approaches implemented by adjusting the residents' characteristics. The primary requirements for education are durable learning, allow intensive interaction, and enable learning-by-doing to establish new habits and improve performance. The fundamental goal of the education is to enable the transformation of intrinsic factors on the knowledge level to intrinsic factors on the emotional level. Without the existence of intrinsic factors in the emotional domain, the expected behaviour would not be sustainable. If the emotional domain can reach the maximum level, the behaviour can be sustainable even without being moderated by extrinsic factors. However, achieving such a top level of the emotional domain might be hard to reach. Thus, it is recommended to combine extrinsic and intrinsic factors to ensure sustainable resident participation effectiveness. The relationship between key extrinsic and intrinsic factors is presented in Fig. 3.

AUTHOR CONTRIBUTIONS

Sunarti was responsible for searching the bibliography, selecting the relevant references, coding the references, writing the initial manuscript draft, synthesising the manuscript, revising the final manuscript version. J.H. Tjakraatmadja was responsible for conceptualizing the draft, analysing the references' coding, and reviewing the whole manuscript. A. Ghazali was responsible for the work plan preparation, defining the bibliographic search, conceptualizing the draft, review the whole manuscript. B. Rahardyan was responsible for the selecting the relevant references, analysing the coding of the references, and reviewing the analysis in the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

%	Per cent
3R	Reuse, reduce, recycle
AAA	Ayla aviation academy
e.g.	Exempli gratia/for example
Fig.	Figure
GHG	Greenhouse gas
IGC	International graduate colloquium
MSW	Municipal solid waste
NVIVO R1	A qualitative data analysis software provided by QSR International
LPDP	*Lembaga pengelola dana pendidikan*

PAYT	Pay as you throw
PBC	Perceived behavioural control
PET	Polyethylene terephthalate
PKM	People and knowledge management
SBM	School of business management
UAE	United Arab Emirates
USD	United States dollar
WM	Waste management

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