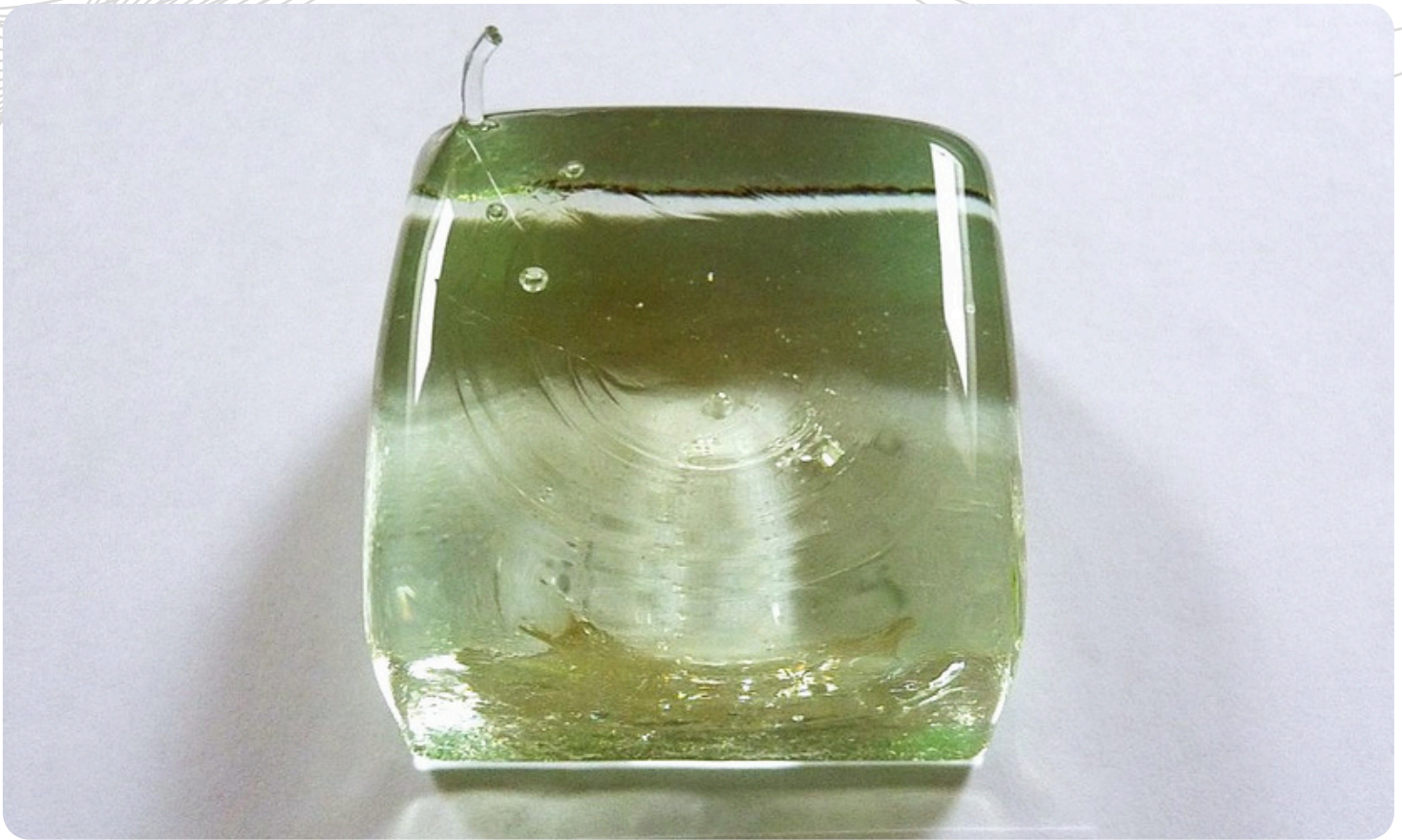




Environment and Natural Resources Journal

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Illuminating sustainability, a glowing molten glass crafted from Brunei's Tutong White Sands achieves 90.2% solar transmittance for photovoltaic applications. This high-silica resource offers a promising pathway for economic diversification and highlights the balance needed between mineral development and the protection of a rare tropical heath ecosystem.

Source: Gödeke SH, Md Izahr Ramahdi NSH, Abas PE, Jaya AA, Suhip MAAH, Walter J, Hensch G, Deubener J. The white sands of Tutong - A high quality sand suitable for photovoltaic applications. Environ. Nat. Resour. J. 2026;24(5):631-641.



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Environment and Natural Resources Journal (EnNRJ) is a peer-reviewed journal which provides a platform for exchanging and distributing knowledge and cutting-edge research in environmental science and natural resource management to academicians, scientists, and researchers.

The scope of the journal covers the integration of multidisciplinary sciences for prevention, control, treatment, environmental clean-up, and restoration. The study of existing or emerging problems related to the environment and natural resources in Southeast Asia and the development of innovative knowledge and/or creative recommendations for mitigation measures and sustainable development are emphasized. The subject areas are diverse, but specific topics of interest include:

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Comparative Analysis of Dissolved Air Flotation and Sedimentation Processes for Treating High Turbidity Waters in Colombia

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ABSTRACT

Dissolved air flotation (DAF) is a prominent technology that permits the treatment of water using higher hydraulic loading rates and lower retention times than sedimentation (SED). This study presents a comparative evaluation of DAF and SED for the treatment of two high-turbidity surface water sources (14-50 NTU) in Colombia. The water samples analysed were collected from the Chiquinquirá River (CR) and the Quebrada Madron Creek (QM), both located in Boyacá, Colombia. The optimal coagulant dosages were identified as 30 mg/L of aluminium sulphate for CR and 60 mg/L for QM using jar testing. Under these conditions, the turbidity removal efficiencies were 86% for DAF and 93% for SED in CR, and 91% for DAF and 93% for SED in QM. The apparent colour removal reached 86% for CR and 83% for QM. The removal of the ultraviolet absorbance at 254 nm (UV₂₅₄), used as a surrogate for natural organic matter (NOM), was 67% for SED and 64% for DAF in CR, with both processes achieving 73% removal in QM. Overall, SED consistently outperformed DAF in turbidity removal for both source waters, while the apparent colour and NOM reductions were comparable between the two technologies. The findings from this work provide valuable insights for optimizing the clarification processes in drinking water treatment plants managing high-turbidity surface waters in Colombia.

HIGHLIGHTS

This study compares two clarification processes, namely, sedimentation and dissolved air flotation, for the removal of high turbidity in water. Furthermore, the efficiency of both methods in eliminating natural organic matter from the treated samples is evaluated and compared. The results highlight the specific advantages of sedimentation over dissolved air flotation when applied two high-turbidity surface water sources.

1. INTRODUCTION

Colombia is recognized as one of the richest countries in terms of freshwater resources globally (World Bank, 2022), possessing a potential annual water extraction capacity of approximately 13 billion cubic meters (Domínguez et al., 2010). However, these water sources are adversely affected by the mineral extraction activities in artisanal mining, which can introduce large quantities of solids and heavy metals, significantly diminishing their suitability as source waters for potable water production (Casso-Hartmann et al., 2022; Caballero-Gallardo et al., 2022; Wright et al., 2014). Drinking water treatment plants

(WTPs) typically employ processes such as coagulation, flocculation, sedimentation (C/F/SED) or, dissolved air flotation (C/F/DAF) (Teixeira and Rosa, 2006; Zou et al., 2011) coupled with conventional filtration, or membrane filtration and chlorine disinfection (Edzwald and Haarhoff, 2011; Vlaski, 2020).

Dissolved air flotation (DAF) is a clarification technology that has been effectively integrated globally into the drinking water treatment sector (Khiadani et al., 2014; Pera do Amaral et al., 2013). Unlike sedimentation (SED), which relies on gravity to achieve the separation of particles and floc

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agglomerates from water, DAF uses microbubbles to facilitate the separation (Kempeneers et al., 2001; Duan et al., 2025; Han et al., 2024; Benjamin and Lawler, 2013). In contrast, SED is considered more appropriate for river waters exhibiting mineral turbidity below 100 NTU. Nevertheless, there are no reported studies directly comparing the performance of DAF and SED for treating waters with turbidity in the intermediate range of 10 to 50 NTU in Colombia. DAF technology is generally recommended for the treatment of raw waters with turbidity levels up to 50 NTU, although its upper operational limit has been reported to reach as high as 100 NTU with short flotation times (Benjamin and Lawler, 2013). Other studies, however, have suggested that DAF performs optimally when treating raw waters with turbidity below 20 NTU (Edzwald and Haarhoff, 2011). A process selection diagram proposed by (Valade et al., 2009) indicates that DAF is suitable for waters with either mineral or non-mineral turbidity below 10 NTU, and that it can also be effectively applied to reservoir waters with non-mineral turbidity below 100 NTU. Comparative studies have assessed the performance of SED and DAF on various water sources, including reservoirs and rivers, which were all characterized by low turbidity, alkalinity and colour (Chu et al., 2011; González-Galvis et al., 2024). Other studies have compared the two clarification processes in terms of their efficiency in removing algae, cyanobacteria, disinfection by-product precursors (DBPs), and *Cryptosporidium* (French et al., 2000). A comparison of these two treatment processes has also been carried out to determine the most effective option as a pre-treatment stage for membrane filtration (Ladouceur and Narbaitz, 2022).

The flocculation stage, which serves as a pre-treatment for both SED and DAF, is typically designed with hydraulic retention times (HRT) ranging from 10 to 30 min (Crittenden et al., 2012). However, investigations regarding the influence of flocculation duration on DAF for treating low-turbidity waters revealed that just 5 min may suffice for effective turbidity removal (González-Galvis et al., 2024; Edzwald, 1995). Conversely, SED is generally designed with an HRT of 1.5 to 4 h, although laboratory jar tests are often performed with sedimentation times of 20 to 30 min (Chemeda and Fitamo, 2025). While full-scale DAF uses short separation times in line with those used in laboratory jar testing experiments, the situation is much different for full-scale SED units tanks because of allowance for

turbulence, density currents, dead zones and room for sludge storage. Studies have addressed the optimal sedimentation durations for turbidity reduction using a jar test apparatus (Chemeda and Fitamo, 2025). However, there is a lack of research concerning the impact of flocculation time on DAF and SED when treating highly turbid waters. Consequently, the primary objectives of this research are to: 1) conduct a comparative study of DAF and SED for the treatment of two distinct natural surface waters with high turbidity levels (14 NTU to 50 NTU) in Colombia utilizing bench-scale DAF and SED jar test apparatus; 2) perform jar tests with an aluminium sulphate-based coagulant to determine whether the optimal coagulant dosage identified for SED is consistent with that required for DAF; 3) compare the effects of 10 and 15 min of flocculation time on turbidity removal efficacy in both SED and DAF for both water types; and 4) evaluate the impact of three different sedimentation durations (15, 20, and 30 min) on the turbidity removal for both water types.

2. METHODOLOGY

2.1 Water tested

The experiments were conducted utilizing two distinct surface water sources, namely, the Chiquinquirá River (CR) and b) the Quebrada Madron Creek (QM), which were characterized by high turbidity levels (ranging from 14 NTU to 50 NTU). Water samples were collected from locations nearest to the roadway along the CR and QM basins. The CR is a small river that traverses the Town of Chiquinquirá, situated in the Boyacá department of Colombia, before flowing into the larger Suárez River. While the Suárez River serves as a primary water source for Chiquinquirá, the CR could potentially serve as an alternative water source in the future. Conversely, the QM is a nearby small stream, water samples were collected 8 km from the city center. The water from the QM is used primarily for agricultural activities, such as crop irrigation, but it holds potential for future use as an alternative drinking water source. Water samples were collected during two separate campaigns in February and March 2023. For this study, six buckets, each containing 20 liters of water from both the CR and QM sources, were collected during each sampling campaign. The samples were stored at a controlled temperature of $4 \pm 1^\circ\text{C}$ to prevent biological degradation of the solids and organic matter before analysis. Figure 1 illustrates the locations of the CR and QM in relation to the Town of Chiquinquirá.

2.2 DAF and SED jar test

Coagulation, flocculation, and dissolved air flotation (DAF) jar tests were conducted following the protocol established by (Zou et al., 2011), which consists of the following stages: (1) rapid mixing at 100 rpm (shear rate (G) of 368 1/s) for 1 min; (2) slow mixing at 40 rpm ($G=67$ 1/s) for 15 min; and (3) flotation for a duration of 10 min. Previous research has indicated that variations in the recycle ratio (RR)

and saturator pressure (SP) do not significantly influence the turbidity removal of a bench-scale DAF apparatus (González-Galvis and Narbaitz, 2022). Consequently, typical values RR and SP were used (i.e. RR of 10% by volume using deionized water and SP of 70 PSI) for all the tests. The SED jar tests were carried out under the same rapid and slow mixing conditions as those applied in the DAF tests, with a settling period of 20 min.

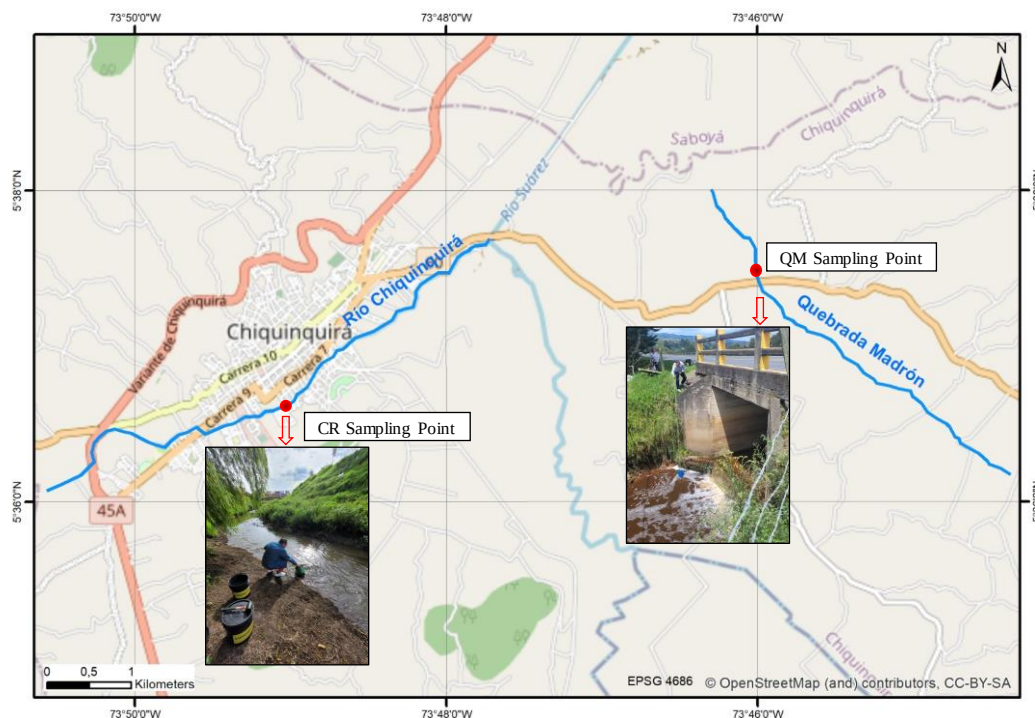


Figure 1. Localization of CR and QM with reference to the Town of Chiquinquirá

The, C/F/SED and C/F/DAF experiments considered aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$) dosages of 30, 40, 50, and 60 mg/L to treat the raw CR water and 60, 70, 80, and 90 mg/L for the raw QM water. Following the C/F/SED and C/F/DAF experiments, the turbidity, pH, apparent colour, and ultraviolet absorbance at 254 nm (UV_{254}), serving as an indicator for the aromatic components of the NOM, were measured immediately using standardized methods for water examination (APHA, 2017). The C/F/DAF experiments were replicated to ensure result reliability, with data reported as the arithmetic average of the two trials. The Figure 2 illustrates the DAF jar test setup and the corresponding flotation procedure.

2.3 Floc settling velocity test

The floc settling velocity (SV) tests were performed using a standard jar test apparatus equipped with 2-liter round beakers. A series of experiments were conducted to evaluate the SV of the flocs by measuring the turbidity following varying settling times ranging from 1.5 min to 30 min (1.5, 4.3, 7.0, 10, 15, 20, and 30 min). The SV experiments were performed at the optimal coagulant dose previously determined for treating the CR and QM water samples, respectively. Rapid mixing was carried out at 100 rpm ($G=368$ 1/s) for a duration of 1 min, followed by slow mixing at 40 rpm ($G=67$ 1/s). For detailed methodology regarding the procedure for standard jar tests, refer to (Pivokonský, 2022).

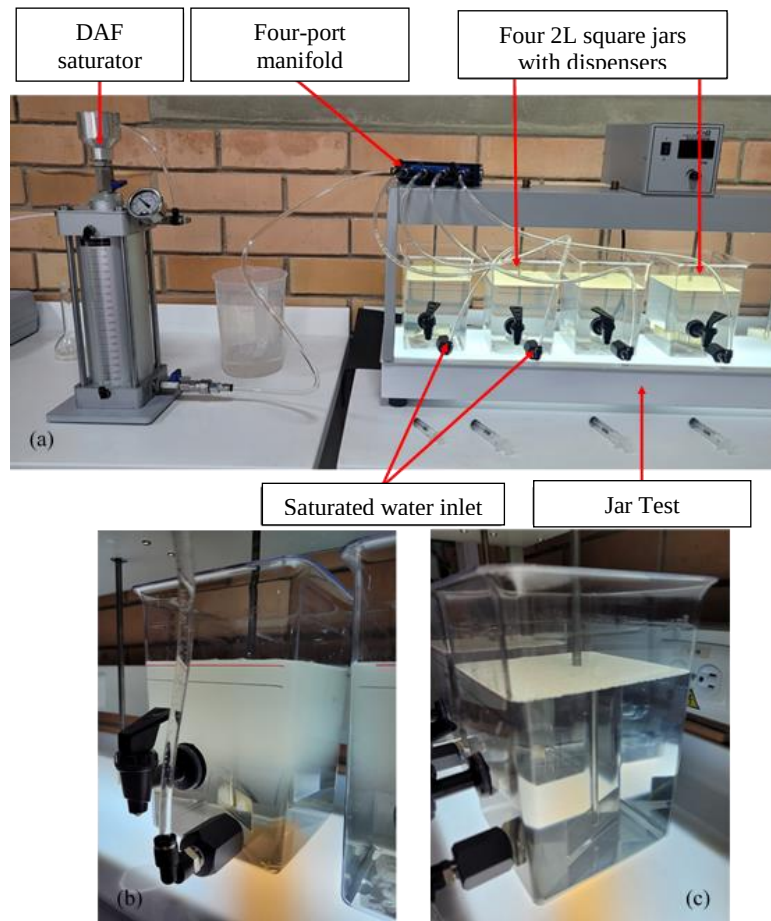


Figure 2. Experimental Setup: (a) DAF jar test apparatus; (b) bubble generation device; and (c) DAF white-water blanket

2.4 Flocculation time impact on turbidity removal

The formation of flocs during the coagulation and flocculation is known to significantly influence the turbidity removal. Factors such as floc size, structure, and density are affected by the agitation intensity, polymer concentration, mixing time and solids concentration during flocculation (Klimpel and Hogg, 1986). Consequently, this research investigated two distinct flocculation times (FT) of 10 min and 15

min to evaluate their effects on turbidity removal. The FT experiments were conducted using the optimum coagulant doses identified for treating the CR and QM water samples, respectively. Rapid mixing was performed at 100 rpm ($G=368$ 1/s) for 1 min, followed by slow mixing at 40 rpm ($G=67$ 1/s) during the respective flocculation times. Figure 3 provides a summary flow diagram depicting the study design and methodology.

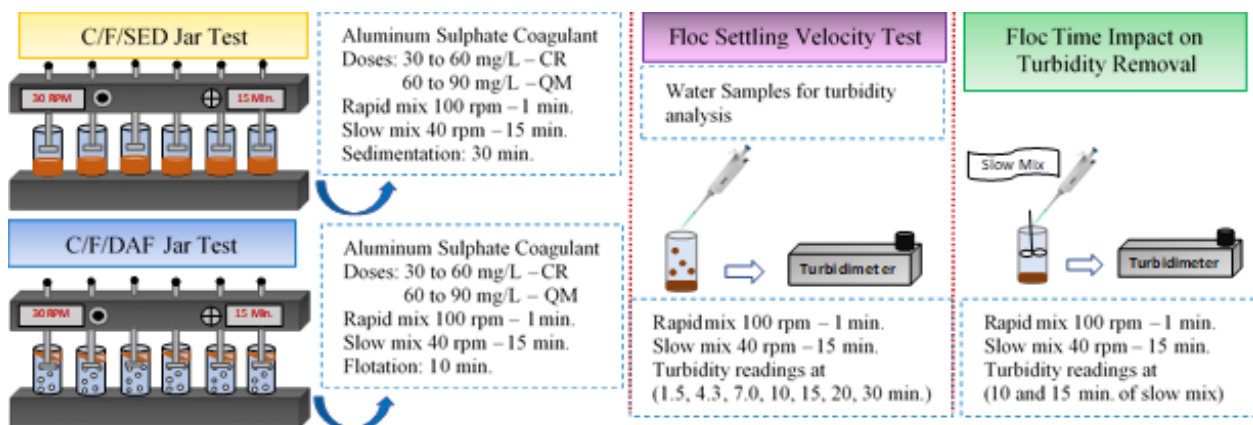


Figure 3. Flow diagram of the study design and method

2.5 Analytical methods

The pH of all water samples was measured using a HANNA HI9125 pH meter (Smithfield, Rhode Island, USA). The turbidity and apparent colour were determined using a Nanocolour® VIS II spectrophotometer (MACHEREY-NAGEL Inc., Allentown, PA, USA). Prior to analysis, the nephelometric turbidity meter was calibrated with 0.1 NTU and 20 NTU standards provided by MACHEREY-NAGEL Inc. The minimum turbidity detectable by the instrument was 0.1 NTU, with a reported measurement repeatability of $\pm 1\%$ or ± 0.01 NTU, as specified by the manufacturer. The ultraviolet absorbance at 254 nm (UV_{254}) was measured using the same Nanocolour® UV/VIS II spectrophotometer, operating within a wavelength range of 190-1,100 nm. Before UV_{254} analysis, the water samples were filtered using 0.45 μm syringe filters (Membrane Solutions AUBURN, WA, USA) and analysed using a 1.0-cm path length quartz cell. The total hardness, alkalinity, and heavy metal concentrations were determined using an upgraded drinking water test kit (Tespert Biotechnology Co, Ltd. Wanchai, Hong Kong).

3. RESULTS AND DISCUSSION

Table 1 presents the characterization of the raw CR and QM waters collected during the sampling campaigns in February and March 2023, respectively. The reported water quality parameters correspond to the arithmetic average of three replicate measurements for each sample. A notable difference in turbidity levels was observed between the two sources, with QM exhibiting higher turbidity values than CR. The turbidity of the raw CR water (15.8 NTU) is primarily attributed to surface runoff from agricultural activities, as agricultural land use accounts for over 80% of the 129.16 km² CR basin (CAR, 2006).

The high turbidity of the raw QM water is primarily attributed to the presence of suspended solids and particulate matter originating from the runoff of agricultural soils within the surrounding basin. Additionally, the apparent colour of the QM is quite elevated (i.e., 819 Pt-Co), markedly higher than that observed in the CR samples. The colour of the QM source water is a yellowish-brown hue, characteristic of the presence of iron (Fe), which was found to be present at a concentration of 2.0 mg/L as Fe.

Table 1. Raw water characterization of the CR and QM

Parameter	CR (February 2023)	QM (March 2023)	Colombian Decree 2115/2007
pH	7.33 $\pm$ 0.06	6.43 $\pm$ 0.12	6.5-9.0
Turbidity (NTU)	15.8 $\pm$ 0.66	44.2 $\pm$ 1.83	2.0
Alkalinity (mg/L as CaCO ₃)	40	10	200
Apparent colour (Pt-o)	237 $\pm$ 12.8	819 $\pm$ 29	15
UV_{254} (1/cm)	0.21 $\pm$ 0.02	1.29 $\pm$ 0.02	NR
Total hardness (mg/L)	50	50	300
Nitrate (mg/L as NO ₃)	25	0.0	10
Iron (mg/L as Fe)	0.0	2.0	0.3
Nickel (mg/L as Ni)	0.0	5.0	0.02

The presence of iron in the surface waters is influenced by the soil composition within the basin as well as the decomposition of organic matter such as leaves, and other plant material (Civardi and Tompeck, 2015). Elevated Fe concentrations in drinking water have been associated with adverse health effects, including hemochromatosis, liver cirrhosis, and chronic fatigue (Chaturvedi et al., 2014). Potentially lower cost alternatives for iron removal may include aeration, chlorination, or hydrogen peroxide, as well as conventional softening, filtration and DAF (Vries et al., 2017; Pacini et al., 2005).

The apparent colour of the CR water was notably high, measuring 237 Pt-Co units, with a characteristic brownish hue attributed to the presence of crop residues and the decomposition of plant material from adjacent forested areas. The nitrate concentration in the raw CR water was 25 mg/L as NO₃⁻, a level is considered relatively high and inappropriate for human consumption without prior treatment. This elevated concentration represents a potential health risk for populations using this water without adequate treatment. Nitrate contamination in surface waters is primarily linked to the use of agricultural fertilizers and animal manure. When

present at elevated concentrations, nitrates can have significant adverse health effects (Ward et al., 2018) including: (1) infantile methemoglobinemia; (2) increased risk of colorectal, bladder, and breast cancers; (3) thyroid dysfunction; and (4) neural tube defects (Ward et al., 2018; Grout et al., 2023). Water treatments for nitrates removal include membrane filtration and activate carbon adsorption (Li et al., 2024; Zeggar et al., 2023).

As shown in Table 1, the QM water contains nickel (Ni) at a concentration of 5.0 mg/L, which substantially exceeds the maximum permissible limit established by Colombian drinking water regulations (0.02 mg/L as Ni). The presence of Ni in surface waters is often associated with runoff carrying particulate matter, as well as the weathering and dissolution of nickel-bearing rocks and soils (WHO, 2005). Nickel exposure has been associated with various adverse health effects in humans, including gastrointestinal disturbances (nausea, vomiting, and diarrhea), neurological symptoms (such as dizziness, fatigue, and headaches), respiratory problems (shortness of breath), as well as reproductive, developmental, and immunological effects, including allergic contact dermatitis (WHO, 2005). In addition, prolonged exposure to elevated concentrations of nickel, particularly in its sulfidic and oxidic forms, has been associated with an increased risk of lung and nasal cancers (WHO, 2005).

Conventional water treatment processes (C/F/SED), coupled with filtration have been shown to achieve nickel removal efficiencies ranging from 35% to 80% (Maleki et al., 2005). Factors such as elevated pH (>7.0), high turbidity, and substantial concentrations of humic substances have been reported to enhance the Ni removal efficiency (Rosińska and Dąbrowska, 2016).

3.1 Comparison of C/F/DAF and C/F/SED jar test results for turbidity removal

Figures 4(a) and 4(b) present the optimal coagulant doses identified for turbidity removal by C/F/DAF and C/F/SED for the CR and QM waters, respectively. As shown in Figure 4(a), the optimal alum dose for treating CR was 30 mg/L as aluminium, represented by blue squares for SED and red triangles for DAF. At this dosage, the residual turbidity for DAF was 2.10 NTU, corresponding to a removal efficiency of 86%, while for SED, the residual turbidity was 1.30 NTU, yielding a removal efficiency of 93%. An independent t-test comparing the turbidity removal

efficiencies between SED and DAF for CR demonstrated that SED (91%) achieved statistically greater removal than DAF (86%) ($p < 0.05$). Therefore, for the CR water, SED exhibited superior turbidity removal performance compared to DAF. These results are consistent with the guidance provided by (Edzwald and Haarhoff, 2011), as well as by (Valade et al., 2009). Coagulant doses below 30 mg/L were also evaluated for the treatment of CR in the jar tests, however, due to their poor turbidity removal efficiency, the corresponding results are not presented in this study.

Figure 4(b) shows that the best coagulant dose for QM was 60 mg/L for both SED (blue squares) and DAF (red triangles). After treatment, SED reduced turbidity to 3.30 NTU (93% removal), while DAF reached 4.50 NTU (90% removal). An independent t-test confirmed that the turbidity removal efficiency of SED (93%) was statistically significantly greater than that of DAF (90%) ($p < 0.05$), indicating that SED also outperformed DAF for the treatment of QM. Additionally, Figure 4(b) shows that increasing the coagulant dose beyond 60 mg/L did not lead to further improvements in turbidity removal for QM. Coagulant doses below 60 mg/L were also evaluated for the treatment of QM in the jar tests, however, due to their poor turbidity removal efficiency, the results are not presented in this study. It is noteworthy that the optimal coagulant dose for CR (30 mg/L) was substantially lower than that required for QM (60 mg/L). This difference in optimal dosages may be attributed to variations in the raw water characteristics of the two sources, particularly turbidity and pH, as summarized in Table 1. Although SED demonstrated statistically superior performance, the turbidity removals achieved by DAF were only slightly lower. Accordingly, DAF can also be considered a feasible process for treating the high turbidity waters used in this study.

3.2 Coagulant dose impact on the final pH

Figure 5(a) illustrates the effect of the varying coagulant doses on the pH of the coagulated raw water from the CR. For CR, all tested coagulant doses resulted in pHs above 6.5, as indicated by the green shading in Figure 5(a). In contrast, Figure 5(b) shows that for QM, all the tested coagulant doses resulted in a substantial reduction in pH, decreasing from 6.43 to 5.57, as indicated by red shading. This is the result of the higher coagulant dose, the greater alkalinity consumption by the coagulant, and the lower raw

water alkalinity. As a result, post-coagulation pH adjustment will be necessary for QM to ensure

compliance with the minimum Colombian drinking water quality standards of 6.5 (Table 1).

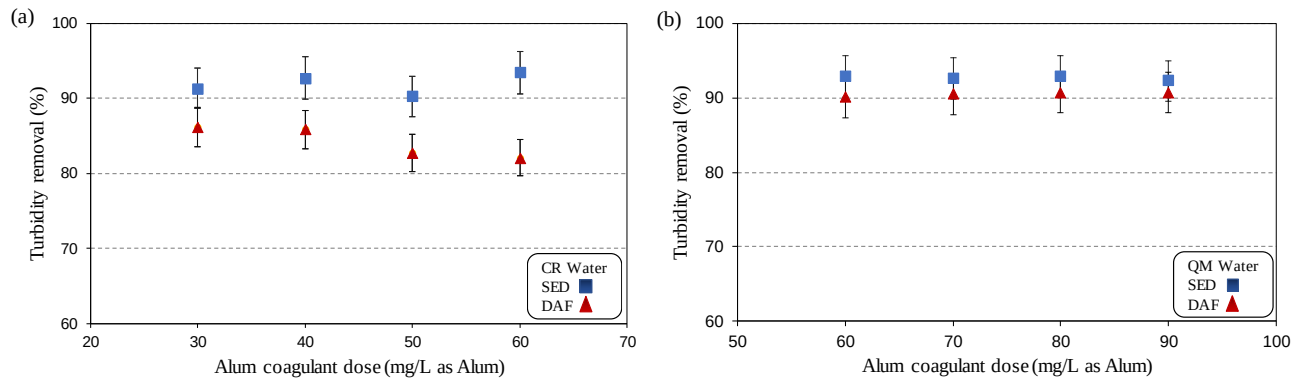


Figure 4. Turbidity removal for the SED and DAF jar test treating: (a) CR; and (b) QM. (error bars indicate one standard deviation) (n=2)

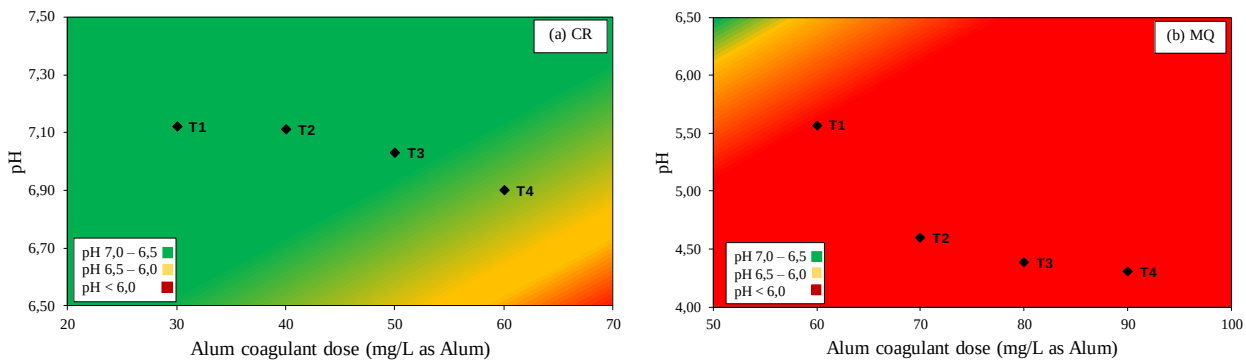


Figure 5. Impact of coagulant dose on treated water pH for: (a) CR; and (b) QM (T indicates the turbidity removal with the optimal coagulant dose)

3.3 Floc settling velocity test

Figure 6(a) presents the concentration of flocs remaining in the jar after various sedimentation times using the optimal coagulant dose of 30 mg/L for the treatment of CR water. The settling velocity of the flocs was indirectly assessed using the residual turbidity measurements. Water samples for turbidity analysis were withdrawn using a 10 mL pipette positioned about 1 cm below the surface of the water in the 1 L beaker. After 10 min of sedimentation, approximately 30% of the flocs remained suspended in the jar, corresponding to a turbidity of 4.84 NTU. For longer sedimentation durations of 15, 20, and 30 min, a gradual settling of very small, low-density floc particles was observed. The corresponding percentages of remaining flocs were 16% (2.63 NTU), 14% (2.21 NTU), and 11% (1.84 NTU), respectively. The final turbidity achieved after 30 min of sedimentation was 1.84 NTU, representing an 89% turbidity removal efficiency. This result is considered satisfactory, as it meets the Colombian regulatory limit of ≤ 2.0 NTU for treated water (Table 1), even prior to

the filtration stage, which is expected to further improve the final turbidity.

A settling velocity test was also conducted using QM water to assess the sedimentation behaviour of the floc particles using the optimal coagulant dose of 60 mg/L (Figure 6(b)). The results in Figure 6(b) show that the flocs formed at this optimal dose settled quickly, presumably because of their high density and compactness. Specifically, 81% of the floc population settled within the first 1.5 min, resulting in a turbidity of 7.52 NTU. After 10 min of sedimentation, the turbidity further decreased to 3.65 NTU, corresponding to a removal efficiency of 91%. This result suggests that a sedimentation time of 10 min was sufficient to achieve turbidity removal comparable to that obtained by DAF (90%), as indicated by the red triangles in Figure 4(b). Sedimentation times of 15 and 30 min yielded only marginal improvements in turbidity reduction, with final turbidity values of 2.48 NTU and 2.43 NTU, respectively, corresponding to a removal efficiency of approximately 94% in both cases.

The formation of large flocs, as observed through visual inspection during the treatment of QM, is likely attributable to sweep flocculation processes.

This mechanism likely enhanced by the precipitation of iron and nickel compounds present in the raw water (Tang et al., 2016; Bora and Dutta 2019).

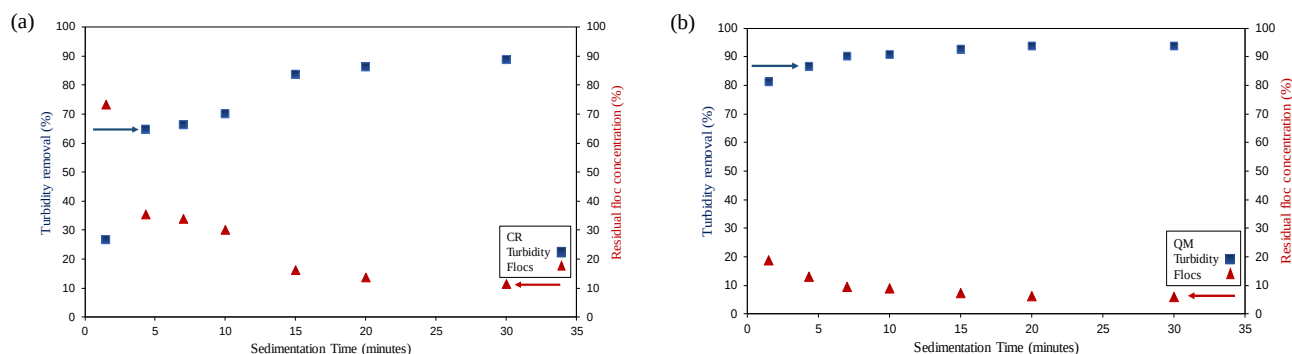


Figure 6. Impact of sedimentation time on residual floc concentration and turbidity removal for: (a) CR; and (b) QM

3.4 Flocculation time impact on turbidity removal

An efficiently conducted clarification process enhances subsequent treatment stages, such as conventional granular filtration or membrane filtration, by extending filtration run times, reducing the frequency of backwashing cycles, and minimizing membrane fouling (Jiao et al., 2017; Malkoske et al., 2020). Accordingly, this study investigated the impact of two different flocculation times on the treatment performance for CR and QM waters. As shown in Figure 7(a), the flocculation time greatly impacted the turbidity removal by SED when treating CR.

Increasing the flocculation time from 10 min to 15 min led to a 6.5% increase in turbidity removal, corresponding to 1.20 NTU. The size and structure of the flocs formed during the coagulation-flocculation process depend on several factors, including raw water

characteristics (e.g., turbidity, pH, alkalinity, temperature, and NOM concentration and composition), as well as operational parameters such as coagulant dose and type, velocity gradient, and flocculation time (Wang et al., 2020; González-Galvis et al., 2022). In this case, the flocculation time played a critical role in enhancing the turbidity removal by SED (Figure 7(a) blue bars). The flocculation time also influenced turbidity removal by DAF when treating CR. As shown in Figure 7(a) (red bars), extending the flocculation time from 10 to 15 minutes resulted in a modest improvement of approximately 8% in turbidity removal efficiency during the DAF process. Nevertheless, a flocculation time of 10 minutes can be considered adequate to achieve satisfactory results with the tested conditions.

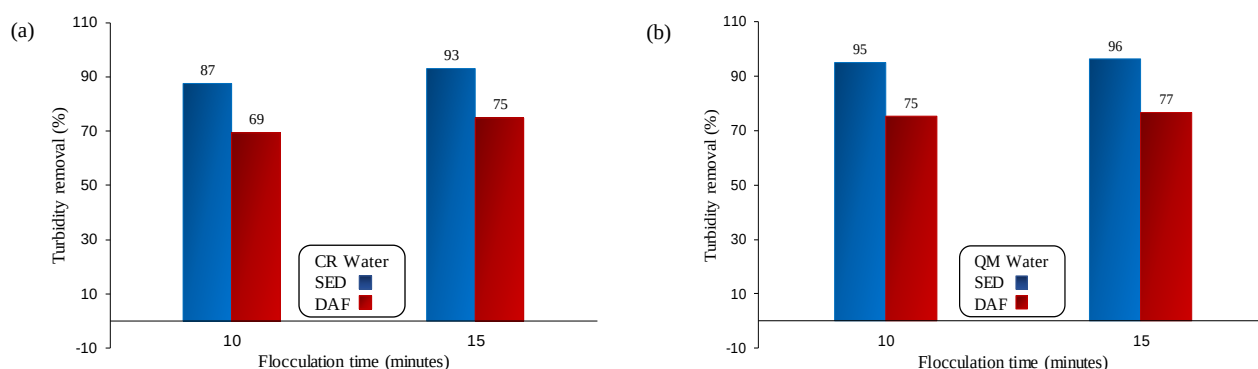


Figure 7. Impact of flocculation on turbidity removal by SED and DAF for: (a) CR; and (b) QM

In DAF systems, the buoyancy force plays a critical role in the interaction between the flocs and bubbles within the separation zone. Smaller flocs experience a proportionally greater buoyancy force

than larger flocs, making them more likely to float. These conditions favour high collision efficiency between small flocs and bubbles, in accordance with the principles described by Stokes' law and the

Reynolds turbulence flow conditions (Basařová and Hubička, 2014; Wang et al. 2021). In this study, well-formed flocs observed following a 15-minute flocculation period for the CR water enhanced buoyancy in the DAF jar tests. This suggests that compact flocs, together with their attached bubble aggregates, exhibited greater overall buoyancy, facilitating more efficient flotation. Furthermore, the probability of floc-bubble collisions likely increased due to the terminal settling velocities of the compact flocs in the DAF jar.

An independent t-test comparing turbidity removal by SED and DAF confirmed a statistically significant difference ($p < 0.05$) between the two processes, with SED achieving 93% turbidity removal, compared to 75% for DAF at a 15 minutes' flocculation time.

Figure 7(b) illustrates the impact of the flocculation time on the turbidity removal for the QM treatment. The results indicate that the flocculation time had no significant effect on either SED or DAF for QM. The formation of well-structured, dense flocs within 10 min of flocculation as observed in the jar was attributed to the raw water characteristics, including high turbidity (44 NTU), high apparent colour (819 Pt-Co), the presence of heavy metals such as iron and nickel (Table 1), and the high optimum

coagulant dose used (60 mg/L as alum). Therefore, for the QM water, a 10-min flocculation time was sufficient to achieve 95% turbidity removal by SED and 75% by DAF. The lower turbidity removal efficiencies by DAF compared to SED for treating the QM water was likely due to the formation of large, heavy flocs with low buoyancy, which yielded poorer separation efficiency of the floc-bubble aggregates in the DAF jar test.

3.5 Sedimentation time impact on turbidity removal

In this study, the impact of three different sedimentation times (10, 20, and 30 min) on turbidity removal was evaluated for the treatment of both CR and QM waters (Figure 8). These time intervals were selected on the basis of recommendations from standard jar test procedures (Pivokonsky, 2022).

Figure 8 illustrates the effect of the sedimentation time on the turbidity removal for CR (red dash pattern bars) and QM (blue pattern bars). For CR water, turbidity removal gradually increased with sedimentation time, reaching 86% removal (2.40 NTU) at 20 minutes. In contrast, the sedimentation time had no significant effect on turbidity removal for the QM, with 10 minutes of sedimentation being sufficient to achieve 95% removal (1.49 NTU).

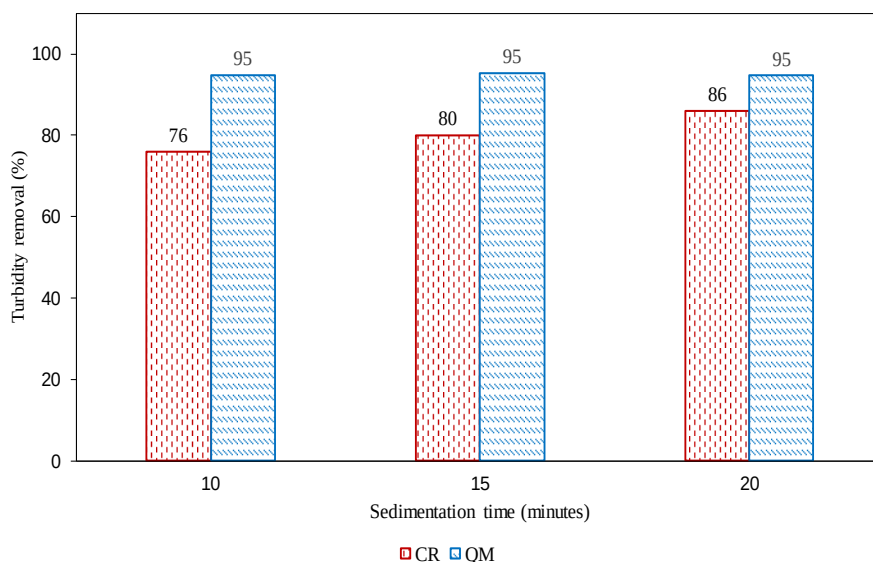


Figure 8. Impact of SED time on turbidity removal for CR and QM waters

The high turbidity removal efficiency observed for QM with just 10 min of sedimentation is likely attributable to the formation of well-structured, compact flocs, (as was visually observed in the jar during the coagulation and flocculation process)

which facilitated rapid settling. Moreover, the combination of the applied coagulant dose and the higher raw water turbidity likely resulted in a floc mass in QM at least twice as large, thereby enhancing

turbidity removal efficiency through the sweep flocculation mechanism.

3.6 C/F/DAF and C/F/SED jar test results for colour removal

To determine the optimal coagulant dose for apparent colour removal (i.e., unfiltered water samples) in both the CR and QM water sources, C/F/DAF and C/F/SED jar tests were performed (Figure 9(a) and Figure 9(b)).

The optimum coagulant dose for the removal of apparent colour in CR water was found to be the same as the optimum for turbidity removal (i.e., 30 mg/L of aluminium sulphate) for both the SED (blue squares)

and DAF (red triangles) treatments (Figure 9(a)). The percent reduction in apparent colour for CR was nearly identical for both clarification strategies, with SED achieving 88% removal and DAF achieving 89%. An independent t-test showed no statistically significant difference between the two treatments ($p < 0.05$). The final apparent colour after coagulation (SED=29 Pt-Co and DAF=25 Pt-Co) for both treatments still exceeded the Colombian regulatory limit of 15 Pt-Co (Table 1). This indicates that additional treatments, such as activated carbon filtration combined with disinfection or oxidation (i.e., chlorination), would be required to remove the remaining colour-causing substances (Wang et al., 2016).

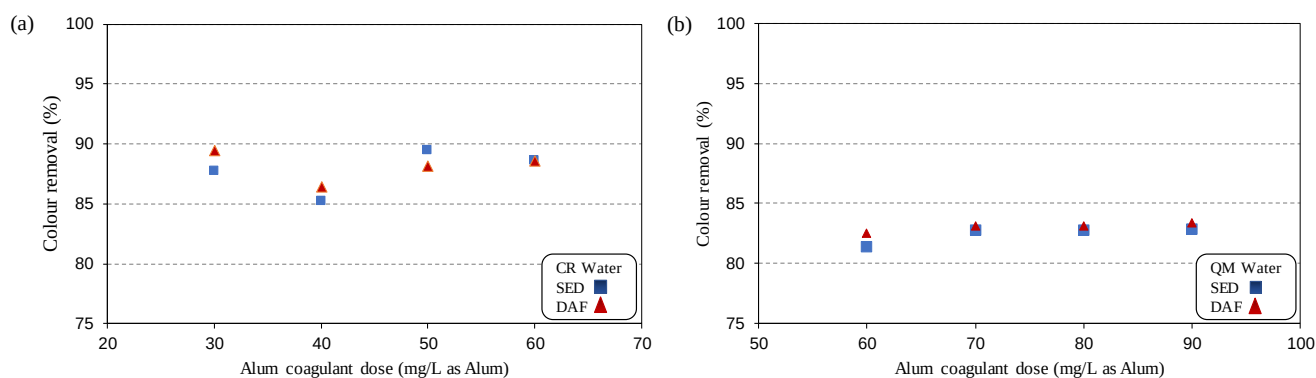


Figure 9. Apparent colour removal for SED and DAF jar test treating: (a) CR; and (b) QM

For QM water, the optimum coagulant dose for the removal of apparent colour was also found to correspond to that for optimum turbidity removal (60 mg/L of aluminium sulphate) for both SED (blue squares) and DAF (red triangles) (Figure 9(b)). The apparent colour removal was relatively similar for both treatments, with SED and DAF achieving an 81% (152 Pt-Co) and 83% (143 Pt-Co) reduction, respectively, at the optimal aluminium coagulant dose. In addition, Fe was completely removed by both the SED and DAF processes. The persistence of high apparent colour in the QM water after coagulation could be associated with residual heavy metals, particularly Ni, that was not fully removed during the treatment process. To further reduce the high apparent colour in surface waters, it is recommended to incorporate chlorine dioxide oxidation and filtration after C/F/SED or C/F/DAF (Civardi and Tompeck, 2015).

3.7 C/F/DAF and C/F/SED jar test results for UV254 removal

Ultraviolet absorbance at a wavelength of 254 nm (UV254) was used as a surrogate measure of the concentration of NOM in both the CR and QM samples. The 254 nm wavelength specifically quantifies the aromatic components of NOM, which can serve as precursors to disinfection by-products (DBPs) (Dong et al., 2023). Figures 10(a) and 10(b) show the removal of UV254 by SED and DAF treatments for CR, while Figures 10(c) and 10(d) illustrate the removal of UV254 by SED and DAF treatments for QM.

Figure 10(a) shows that the UV254 removal with the optimal coagulant dose (i.e., 30 mg/L) for treating CR was 62% for SED and 59% for DAF. Additionally, Figures 10(a) and 10(b) demonstrate that UV254 removal increased gradually with higher aluminium coagulant doses for both treatments.

However, beyond 50 mg/L, there was only limited improvement in UV254 removal. This could be attributed to the low variability in pH across the tested coagulant doses (Matilainen et al., 2010). A one-way ANOVA conducted for the different coagulant doses used to treat CR water showed no statistically

significant difference between UV254 removal by SED and DAF ($p < 0.05$). Thus, the results indicate that UV254 removal for CR water depends mainly on the aluminium coagulant dose rather than on the type of solid-liquid separation process used (Malkoske et al., 2023).

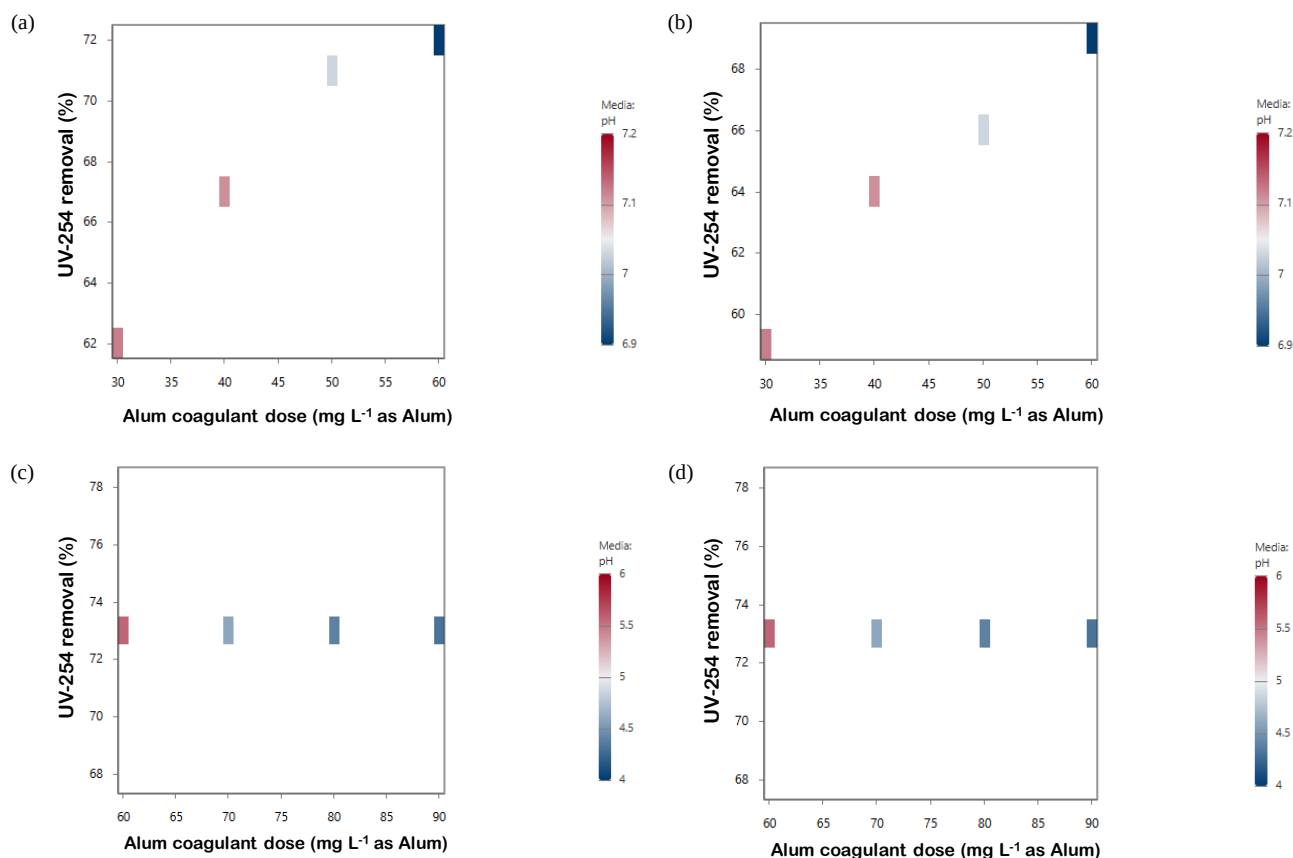


Figure 10. Removal of UV254 absorbance for: (a) SED-CR; (b) DAF-CR; (c) SED-QM; and (d) DAF-QM (Minitab®).

When the QM water was considered, there were also no differences in UV254 removal observed between SED and DAF treatment at the optimal coagulant dose (Figures 10(c) and 10(d)). The high UV254 removal percentage for QM is likely due to the high coagulant dose that created effective sweep floc conditions and contained more aluminium flocs, facilitating removal by adsorption (Matilainen et al., 2010). Reducing the amount of aromatic substances in water is important because it can help reduce the concentration of disinfection by-products (DBPs), such as trihalomethanes (THMs), in drinking water distribution systems (Mustereț et al., 2021). In Colombia, total trihalomethanes (THMs) must not exceed a concentration of 200 µg/L at the extremes of the distribution system.

4. CONCLUSION

This study presents the first comparative assessment of SED and DAF for the clarification of two surface water sources with high turbidity in Colombia specifically, the CR and QM. While both treatment alternatives achieved high turbidity removals, SED was found to consistently outperform DAF, yielding greater turbidity reduction and lower residual turbidities. The flocculation time significantly impacted the turbidity removal for CR. Compared to a 10-minute flocculation period, fifteen minutes of flocculation improved turbidity removal by 6.4% in SED and 8% in DAF. However, for QM water, the flocculation time was found to have minimal impact on turbidity reduction. This is likely due to higher feed turbidity and much higher optimal coagulant dose.

When the impact of sedimentation time was assessed using the CR water, turbidity removal improved with increasing sedimentation time, reaching 86% after 20 minutes. In contrast, for the QM water, the maximum turbidity removal of 95% was achieved after only 10 minutes, indicating that extended sedimentation was unnecessary for this source. The final colour values for all combinations of water and treatment types were found to exceed the Colombian regulatory limits, indicating that the water requires additional treatment, including filtration and chlorination for oxidation (e.g., chlorine dioxide). Future work should explore combined treatment strategies (e.g., advanced oxidation processes, activated carbon filtration) to address the persistent colour and NOM challenges, especially for QM. The UV254 absorbance showed similar removal rates for both SED and DAF. The UV254 removal efficiency was primarily a function of the source water and the coagulant dose rather than the separation method. These findings underline the necessity of integrating additional treatment processes (e.g., oxidation or adsorption) tailored to each source's contaminant profile. Since the optimal coagulant dose for treating QM produced a post-coagulation pH below the Colombian regulatory limit of 6.5, it is recommended to perform a pH adjustment after treatment to ensure compliance with drinking water quality standards and reduce corrosion in the distribution system. In summary, sedimentation demonstrated slightly superior turbidity removal and matched DAF in colour and UV254 reduction. Given its lower operational complexity and comparable efficiency, SED may represent a more robust and context-appropriate clarification method for high-turbidity surface waters where there is unlikely to be space constraints requiring a more compact separation process.

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AUTHOR CONTRIBUTIONS

J. P. González-Galvis participated in the sampling campaigns, conducted the experiments, conceptualized the study, wrote, reviewed, and edited the manuscript. A. M. Jaramillo and B. Pacheco participated in the sampling campaigns and reviewed and edited the manuscript.

DECLARATION OF CONFLICT OF INTEREST

The author declares no competing financial interest.

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Sargassum-Derived Bioplastic for Sustainable Packaging: Evaluation of Mechanical, Thermal, and Barrier Properties

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ABSTRACT

Plastic pollution remains a critical environmental issue due to the persistence of petroleum-based plastics in natural ecosystems. This study evaluates *Sargassum* seaweed, an abundant coastal biomass in Malaysia, as a renewable feedstock for biodegradable bioplastic production. To overcome the inherent limitations of alginate-based bioplastics, glycerol 12.6% (w/w, relative to polymer mass) has been incorporated as a plasticizer, with calcium chloride (2% w/v) as a cross-linking agent. Bioplastic films were produced via alginate extraction, film casting, and drying, and characterized through tensile testing, differential scanning calorimetry (DSC), water absorption, grease absorption, and biodegradability analyses. The modified *Sargassum*-based bioplastics exhibited enhanced tensile strength (maximum force up to 6.67 N), improved elongation at break (up to 31.33%), and increased thermal stability, with a melting temperature of 160°C and degradation onset at 190°C. Swelling, biodegradation, and oil uptake behaviors were governed by the interplay between hydrophilic diffusion and calcium-mediated cross-link stabilization. Complete biodegradation was observed within 30 days in soil. These findings demonstrate that formulation optimization allows *Sargassum*-derived bioplastics to achieve balanced mechanical performance, barrier properties, and environmental degradability. This will enhance their potential for sustainable single-use packaging applications.

HIGHLIGHTS

- Valorization of abundant *Sargassum* seaweed for bioplastic production.
- Enhanced strength and thermal stability via glycerol and CaCl₂ modification.
- Complete biodegradation of films achieved within 30 days of testing.
- Promising eco-friendly alternative for single-use packaging materials.

1. INTRODUCTION

Plastic pollution has emerged as a critical environmental concern, due to the extensive use of non-biodegradable petroleum-based plastics, which can persist in ecosystems for centuries. A major consequence of their persistence is the formation of microplastics, tiny plastic fragments that accumulate in marine and terrestrial environments, posing risks to aquatic life, food safety, and even human health (Khan and Setu, 2022; Putri et al., 2023). These conventional plastics not only contribute to marine pollution and habitat destruction, but also release greenhouse gases

during both production and degradation (Gross and Enck, 2021). In response, bioplastics made from renewable resources have gained attention as a sustainable alternative capable of reducing environmental harm (Nagarajan et al., 2024). In Malaysian coastal regions such as Port Dickson, seasonal *Sargassum* blooms are frequently observed during warmer periods (Chin et al., 2023). While excessive accumulations may lead to beach fouling and temporary disruptions to tourism and fisheries, these biomasses present valuable opportunities for sustainable resource utilization. Recent studies

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highlight the potential of converting *Sargassum* into biodegradable plastics as a practical strategy to reduce dependence on conventional petroleum-based plastics while supporting circular economy principles in local industries (Farghali et al., 2023).

Sargassum contains alginate, a naturally biodegradable polymer suitable for bioplastic production. However, existing research shows that *Sargassum*-based bioplastics often exhibit insufficient mechanical strength and thermal stability, limiting their practical applications (Bullen et al., 2024; Liu et al., 2023). Enhancing these properties through optimized formulations and processing techniques could significantly improve their usability. Research indicates that blending *Sargassum* alginate with biodegradable polyesters like polylactic acid (PLA) or polyhydroxyalkanoates (PHA) yields superior tensile properties while mitigating inherent brittleness (Santana et al., 2024). Glycerol was selected as the plasticizer in this study due to its proven compatibility with polysaccharide-based biopolymers, particularly alginate, and its widespread use in biodegradable film formulations (Hanry and Surugau, 2024). As a low-molecular-weight, hydrophilic plasticizer, glycerol effectively improves polymer chain mobility through hydrogen bonding interactions, thereby enhancing film flexibility and processability (Ben et al., 2022). In addition, glycerol is non-toxic, biodegradable, inexpensive, and readily available, making it suitable for sustainable packaging applications. Compared to alternative plasticizers such as sorbitol or polyethylene glycol, glycerol has been shown to provide a favourable balance between flexibility and mechanical integrity when used at controlled concentrations, while avoiding excessive stiffness or brittleness in alginate-based films (Langit et al., 2019). Cross-linking modifications using calcium chloride (CaCl_2) are particularly effective in enhancing structural rigidity and moisture resistance via ionic-bridge formation between alginate polymer chains (Asmadi et al., 2025). Composite formulations combining *Sargassum* alginate with PLA demonstrate enhanced thermal resistance, with decomposition onset temperatures exceeding 200°C in optimized compositions (Dungani et al., 2021), while cellulose nanofiber reinforcement enhances stability up to 200°C. However, plasticizers like glycerol (20%) can lower thermal resistance to around 140°C (Santana et al., 2024). Cross-linking with CaCl_2 improves thermal (190°C) and mechanical properties compared to non-crosslinked counterparts (Asmadi et al., 2025).

Previous studies have reported a wide range of mechanical performance for bio-based plastics derived from seaweed and alginate composites. For example, *Sargassum*-based alginate films typically show tensile strengths between 2-8 MPa and elongation at break values of 10-40% depending on the type and concentration of plasticizer used (Mohammed et al., 2023). Reinforcement with cellulose nanofibers or PLA has been shown to increase tensile strength up to 15 MPa, while glycerol-rich formulations may reduce strength to below 5 MPa but improve flexibility (Dungani et al., 2021). Calcium chloride cross-linked alginate films often demonstrate improved rigidity with tensile strength values reaching 10-12 MPa and reduced elongation compared to non-cross-linked films (Asmadi et al., 2025). These studies highlight that balancing cross-linking and plasticizer content is essential to achieving both strength and flexibility in bioplastics.

This research aimed to develop improved *Sargassum*-based bioplastics by incorporating glycerol as a plasticizer and calcium chloride as a cross-linking agent to boost mechanical and thermal performance. This study also compared the enhanced bioplastics with conventional packaging plastics and assessed their biodegradability, supporting the development of functional, eco-friendly materials. By addressing the current limitations of *Sargassum* bioplastics, this work contributes to sustainable solutions for plastic pollution. The findings highlight the potential of utilizing Malaysia's natural *Sargassum* resources while advancing environmentally responsible alternatives to traditional plastics.

2. METHODOLOGY

2.1 Sample location

Sargassum seaweed samples were collected from the primary sampling site of Avillion Beach, Port Dickson, Malaysia. Species identification was carried out based on morphological characteristics, including thallus structure, blade shape, presence of air vesicles, branching pattern, texture, and pigmentation. Visual comparisons with established taxonomic descriptions and published identification keys were supported by high-resolution reference images from peer-reviewed literature and authoritative online algal databases. Based on these criteria, the dominant species identified at the sampling site included *Sargassum muticum*, *Padina tetrastromatica*, and *Chondrus crispus*. Among these, *Sargassum muticum* was selected for bioplastic production, due to its

abundance and reported suitability for alginate extraction. Figure 1 presents an overview of the seaweed types identified at Avillion Beach, Port

Dickson, including *Sargassum muticum*, *Padina tetrastromatica*, and *Chondrus crispus*.

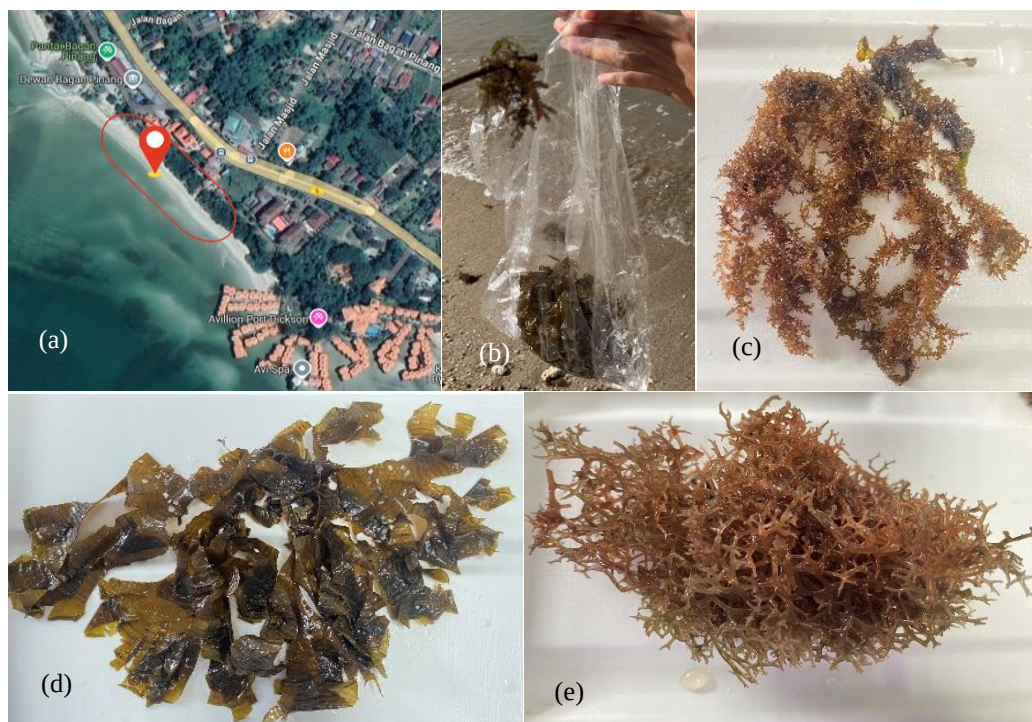


Figure 1. Seaweed types found at Avillion Beach, Port Dickson. a), Location of sample collection. b), Seaweed collection at the shoreline of the beach. c), *Sargassum muticum* (used in this study), d), *Padina tetrastromatica* also known as mermaid's fan seaweed (Palaniveloo et al., 2021). e), *Chondrus crispus* commonly called as Irish Moss (Wilkes, 2022)

2.2 Pre-processing and drying

Sargassum samples were processed according to the previously described method (Alallam et al., 2025) with slight modifications. Each sample was chopped into smaller pieces and dried in an oven at 60°C. After drying, the samples were ground into fine powder using a mechanical grinder to increase surface area for alginate extraction. The resulting powder was passed through a 60 mesh sieve, yielding particles of approximately ~250 µm. The sieved powder was then stored in airtight containers to prevent moisture absorption until further processing.

2.3 Alginate extraction and liquefaction

The alginate extraction was performed as previously described method with slight modification (Alallam et al., 2025). Modifications included reducing extraction temperature to 50°C to prevent polymer degradation, fixing sodium carbonate concentration at 2% (w/v), and limiting stirring duration to 2 h to maintain polymer integrity. Subsequently, the solution was filtered under vacuum to remove solid residues. The liquid collected contains

the extracted alginate. To precipitate the alginate, 150 mL of 2% (v/v) calcium chloride was added to the solution and stirred for 30 minutes until a gel-like precipitate formed.

2.4 Formulation, film casting and drying of bioplastic

The alginate gel-like structure was enhanced by the addition of 12.6% (w/w, relative to polymer mass) of glycerol as a plasticizer, stirred for 30 min at 50°C. The sample was then allowed to cool down for 10 minutes before casting. The *Sargassum* bioplastics mixture was poured into a mold (200 mm × 28 mm) to form a thin and uniform film with an approximate thickness of 0.2 mm. The cross-linking was achieved by spraying 5 ml of 2% diluted calcium chloride solution onto the cast film (Mohammed et al., 2023). Then, the sample was left to air dry for three days, carefully removed from the mold, and stored at room temperature for 48 h under controlled conditions for further testing. This method of film plasticization and cross-linking has been supported in previous studies for improving the structural integrity and moisture

resistance of alginate-based bioplastics (Bouzenad et al., 2024; Elkaliny et al., 2024). The flow process of

the glycerol plasticization, film casting and calcium chloride cross-linking process is depicted in Figure 2.

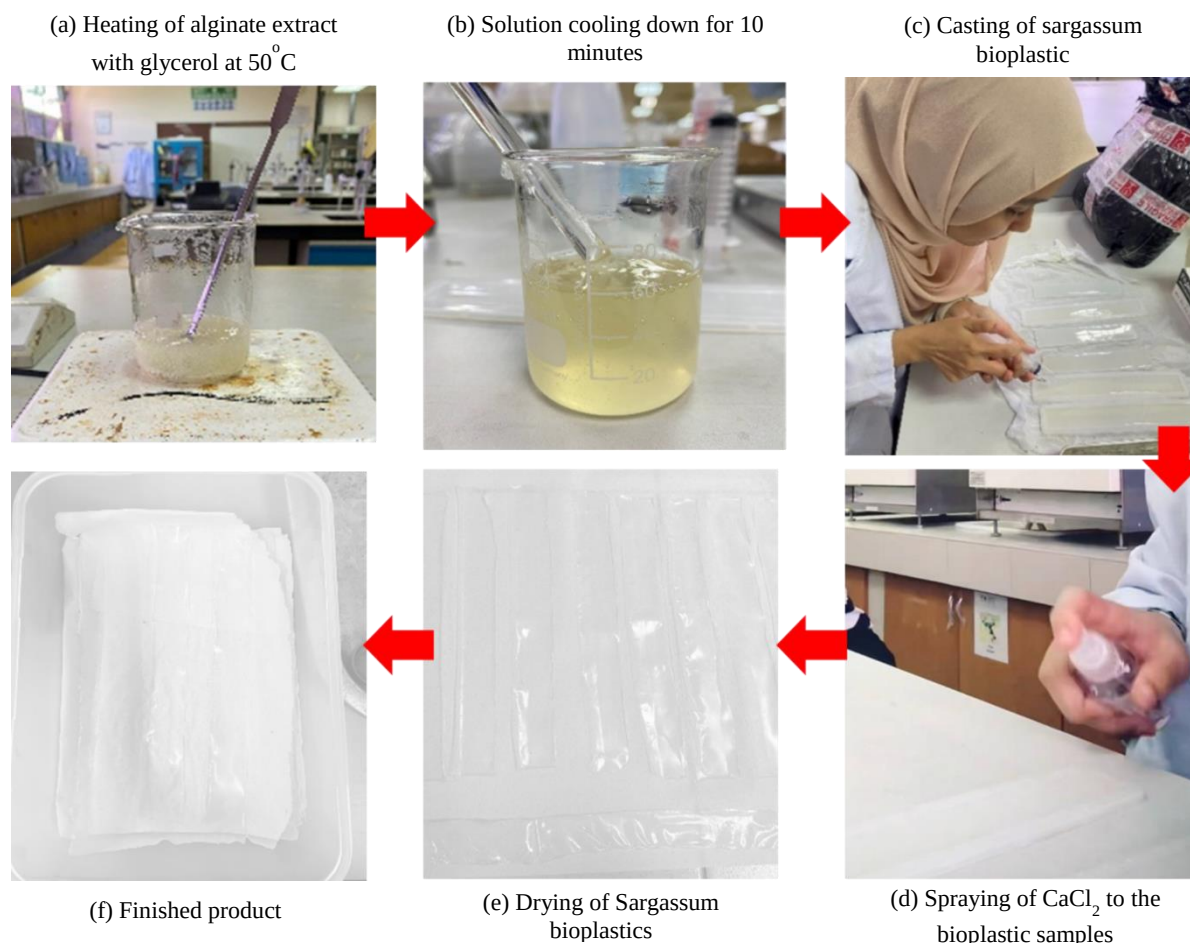


Figure 2. Fabrication process of *Sargassum*-based bioplastic films: (a) heating alginate extract with glycerol at 50°C, (b) cooling for 10 min, (c) film casting, (d) CaCl_2 spraying for cross-linking, (e) air-drying, and (f) final dried bioplastic film

2.5 Mechanical testing

The tensile properties of *Sargassum* bioplastics were evaluated using a textile tensile machine (UTS-Tex-Plus, UTS International, China), following the ASTM D882 standard. The method was adapted from a previous study (Kumari et al., 2024), by adjusting clamp speed to 1 mm min⁻¹ and using duplicate samples due to material availability constraints. Mechanical testing was done in duplicates for both *Sargassum* bioplastic (SB) and conventional plastic (CP). Dumbbell-shape bioplastic samples were clamped into the machine's grips and pulled at a constant rate until fracturing. The machine was set at a clamp speed of 1 mm/min with the sample length 45 mm. A load cell of ID/FS (5/500) was used. Mechanical testing was conducted in duplicate due to material preparation constraints; therefore, tensile data are interpreted as comparative trends rather than statistically validated differences. This method

measured the tensile strength and elongation at break, providing insight into the flexibility and mechanical durability of the films. These properties are especially critical for assessing the bioplastics' feasibility in packaging applications, in which strength and stretchability are essential (Kumari et al., 2024).

2.6 Thermal testing

The thermal behavior of the *Sargassum* bioplastics was assessed using Differential Scanning Calorimetry (DSC 1, METTLER TOLEDO, Switzerland), aligned with ASTM. The experimental procedure was adapted from a previous study (Bauta et al., 2024), with modifications including a heating range of 25-350°C and nitrogen flow rate of 50 mL min⁻¹ to ensure uniform thermal analysis conditions. Firstly, a section of the bioplastic film was cut and trimmed to precise masses within the 5-10 mg range, and the exact mass of each sample (5.4-5.6 mg) was

recorded prior to analysis and is reported in Table 2. The sample was sealed in a 40 μ L aluminium crucible and excess moisture was removed. The DSC system was calibrated using indium as a reference material. Thermal testing was performed in triplicate for the *Sargassum* bioplastic (SB) samples. Both the sample and an empty reference crucible were placed into the DSC chamber. Testing was performed from 25°C to 350°C at a heating rate of 10°C/min under a nitrogen flow rate of 50 mL/min. The DSC curve was used to identify the glass transition temperature (T_g), melting temperature (T_m), and thermal degradation point. After testing, samples were visually inspected for any physical changes, including melting or charring, to assess thermal endurance. Thermogravimetric Analysis (TGA) was not conducted in this study due to equipment limitations; however, the Differential Scanning Calorimetry (DSC) data provided sufficient insight into the bioplastic's thermal transition and stability behavior. Future work could include TGA testing to further quantify the decomposition stages and thermal degradation profile of *Sargassum*-derived bioplastics.

2.7 Water absorption test

The bioplastics underwent a water absorption test following the ASTM D570-98 standard (ASTM, 1999). The method applied was based on previous study (Farhoud et al., 2024), with slight modifications involved extending observation duration to 35 days. Measurements were recorded at 2-5 day intervals to capture long-term absorption behaviour. The *Sargassum* bioplastic (SB) samples were tested in triplicate. They were initially weighed and then fully immersed in 600 mL of distilled water at room temperature (25 $\pm$ 1°C). At regular intervals of 2-5 days, the samples were removed, gently patted dry, and reweighed to monitor the rate and extent of water absorption. This test is crucial for understanding the behavior of the *Sargassum*-based bioplastics under humid or wet conditions, a critical factor in applications such as food packaging or agricultural films.

2.8 Biodegradability test

Environmental compatibility was assessed using the soil burial method in accordance with ASTM D5988 with methodological adaptation (Synani et al.,

2024). Triplicates samples of the *Sargassum* bioplastics (SB) were first weighed and then buried approximately 2 cm deep into organic-rich garden soil (Tarangini et al., 2023). Every week, the samples were removed, cleaned with distilled water, dried at room temperature for 24 h, and reweighed. The percentage of weight loss was calculated to determine the rate of degradation (Equation 1). This method simulates natural environmental conditions and helps to evaluate the biodegradability of the material over time.

$$\text{Biodegradation (\%)} = \left(\frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \right) \times 100 \quad (1)$$

2.9 Grease absorption test

A grease absorption test was carried out to assess resistance to oil penetration. This was based on procedures aligned with ASTM F119-82 (ASTM, 2022), with slight modifications based on the method used by Mohammed et al. (2023). Vegetable oil was heated to four different temperatures (20°C, 40°C, 60°C, 80°C), and 10 mL of the hot oil was poured onto each sample. The bioplastics were allowed to rest for 30 min to permit oil absorption. The samples were weighed before and after oil exposure to calculate the amount of oil absorbed. This test indicates how well the bioplastics can resist grease, which is essential for food-contact applications, especially in packaging.

3. RESULTS AND DISCUSSION

3.1 Mechanical testing

Mechanical testing was conducted to assess the tensile strength and flexibility of the *Sargassum*-based bioplastics. These properties are essential to real-world applications, such as biodegradable packaging and disposable consumer products. In this testing, the conventional plastic (CP) used as control was commercial low-density polyethylene (LDPE) film. Figure 3 presents the tensile test conditions of *Sargassum* bioplastics (SB) and conventional plastics (CP), showing both materials before and after maximum elongation. The results demonstrated that the addition of glycerol as a plasticizer and calcium chloride as a cross-linking agent significantly enhanced the mechanical performance of the samples (Bouzenad et al., 2024; Mohammed et al., 2023).

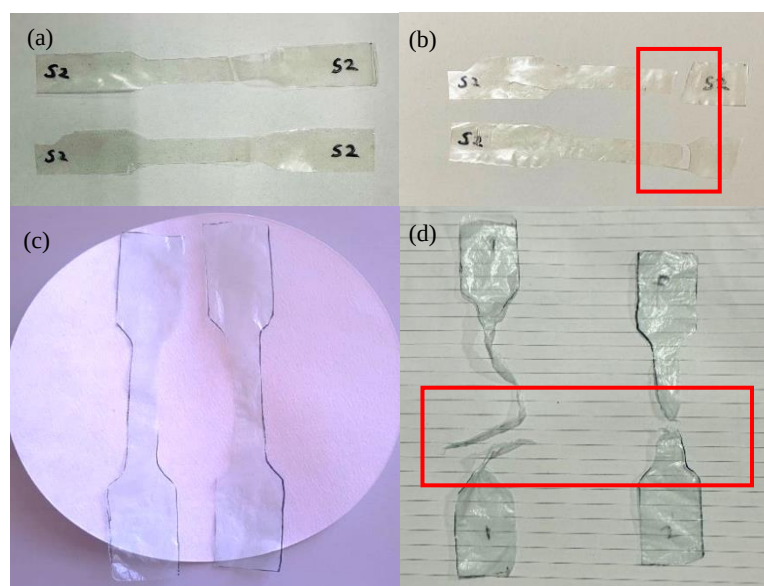


Figure 3. Mechanical tensile test comparison of *Sargassum* bioplastics (SB) and conventional plastic (CP). (a), SB samples before tensile testing. (b), SB after maximum elongation. (c), CP samples before tensile testing. (d), CP after maximum elongation. Red boxes indicate the regions of maximum deformation and fracture, highlighting elongation behaviour and failure points of the tested specimens

Table 1 summarizes the tensile properties of the *Sargassum*-based bioplastic (SB, $n=2$) compared with the conventional plastic reference (CP, $n=2$). The *Sargassum* bioplastic exhibited a mean maximum force of 5.74 ± 1.31 N, elongation at break of $29.00 \pm 3.30\%$, and time-to-failure of 783 ± 89 s. In

contrast, the conventional plastic demonstrated lower tensile resistance (1.86 ± 0.00 N), reduced elongation ($9.67 \pm 2.36\%$), and shorter failure time (261 ± 63.64 s). Under the tested conditions, the *Sargassum*-based film therefore showed greater extensibility and resistance to fracture than the LDPE reference.

Table 1. Tensile properties of *Sargassum*-based bioplastic films compared with the reference conventional plastic control (Low-Density Polyethylene, LDPE)

Sample	Description	Maximum force (N)	Maximum elongation (%)	Time (s)
SB ($n=2$)	<i>Sargassum</i> + Glycerol + CaCl_2 (0.2 M)	5.74 ± 1.31	29.00 ± 3.30	783 ± 89
CP ($n=2$)	Conventional plastic	1.86 ± 0.00	9.67 ± 2.36	261 ± 63.64

The enhanced mechanical performance may be attributed to the complementary roles of glycerol and calcium chloride within the alginate-based matrix (Asmadi et al., 2025; Bojorges et al., 2023; Mohammed et al., 2023; Santana et al., 2024). Glycerol functions as a plasticizer by forming hydrogen bonds with hydroxyl and carboxyl groups along the polymer chains, thereby increasing chain mobility and reducing intermolecular rigidity (Langit et al., 2019). This contributes to improved flexibility and elongation capacity. Meanwhile, calcium ions from CaCl_2 act as ionic cross-linkers, forming electrostatic bridges between alginate carboxylate groups and generating a three-dimensional network structure (Barman et al., 2025). This cross-linked network both limits excessive chain slippage and

enhances tensile integrity and structural stability (Mohammed et al., 2023). A combination of plasticization and ionic cross-linking results in a balanced polymer system capable of exhibiting both moderate strength and improved extensibility (Barman et al., 2025).

Mechanical testing was conducted twice. Therefore, the reported values represent comparative trends rather than statistically validated differences. Additional replications would be required to confirm statistical significance. Nonetheless, the results indicate that incorporation of glycerol and calcium chloride can enhance the mechanical performance of *Sargassum*-derived bioplastics through synergistic molecular interactions. The mechanical behaviour observed supports the potential of this material for

low-load and short-term packaging applications in which moderate strength and flexibility are required.

3.2 Analysis of thermal testing using DSC

Figure 4 presents the DSC thermograms of the *Sargassum*-based bioplastic samples (SB1-SB3) and the conventional plastic control (CP). It should be

noted that SB1-SB3 represent triplicate specimens of the same formulation tested to assess experimental reproducibility. The curves reveal distinct thermal transitions which correspond to the glass transition temperature (T_g), melting temperature (T_m), and onset of thermal degradation, respectively.

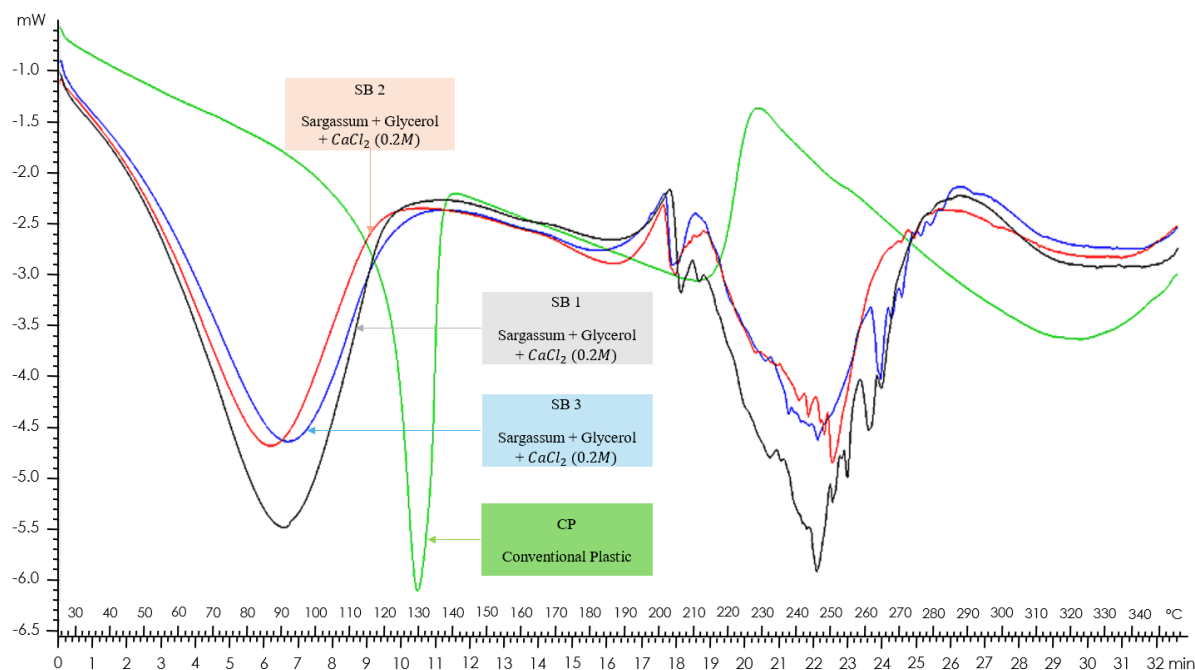


Figure 4. Differential Scanning Calorimetry (DSC) thermograms of *Sargassum*-based bioplastic films compared with the conventional plastic control. SB1-SB3 correspond to triplicate specimens of the same *Sargassum* bioplastic formulation (*Sargassum* + glycerol + CaCl_2 , 0.2 M), while CP represents the conventional plastic reference. The curves show characteristic thermal transitions including glass transition (T_g), melting temperature (T_m), and thermal degradation onset. Small differences among SB thermograms are attributed to experimental variability among replicates.

The first transition observed in the SB samples occurred around 52-55°C and corresponded to the glass transition temperature (T_g), marking the shift from a rigid, glassy state to a more flexible, rubbery state. The relatively moderate T_g values indicate that glycerol acts as a plasticizer, increasing polymer chain mobility by reducing intermolecular hydrogen bonding between alginate chains. Minor variations among SB1-SB3 may be attributed to sample heterogeneity and thermal measurement sensitivity rather than formulation differences.

A second endothermic peak can be observed between 148-160°C, corresponding to the melting temperature (T_m), which reflects disruption of ordered domains within the calcium-cross-linked alginate network. The small variation in T_m among replicates likely reflects differences in local cross-link density and film thickness. These results confirm that ionic

cross-linking contributes to structural stabilization and moderate thermal resistance.

The onset of degradation for the SB samples occurred between 180-190°C, representing breakdown of the polymer backbone and weakening of the cross-linked network. Slight shifts in degradation onset among replicates are considered within expected experimental variation. In comparison, the conventional plastic exhibited higher T_g and T_m values, consistent with its greater crystallinity and synthetic polymer structure. Nevertheless, the thermal performance of the *Sargassum*-based bioplastic would be adequate for low-temperature packaging applications.

Previous studies have similarly reported enhanced thermal resistance in CaCl_2 -cross-linked alginate films due to ionic bridging effects (Abu Ubaidah et al., 2024; Barman et al., 2025; Chakraborty et al., 2022). Although Differential Scanning

Calorimetry (DSC) provides insight into thermal transitions, thermogravimetric analysis (TGA) would further complement these findings by providing

quantitative mass loss profiles and degradation kinetics. Comprehensive thermal characterization is thus recommended for studies incorporating TGA.

Table 2. Differential scanning calorimetry test of *Sargassum* bioplastics

Sample	Description	Glass transition temperature, T_g (°C)	Melting point, T_m (°C)	Onset degradation temperature, (°C)	Enthalpy, ΔH_{cc} ($\frac{J}{g}$)	Observation
SB1 (Rep1)	<i>Sargassum</i> + Glycerol + $CaCl_2$ (0.2 M) Black line, 5.5 mg	55	150	185	Moderate	Moderate thermal profile, relatively stable
SB2 (Rep2)	<i>Sargassum</i> + Glycerol + $CaCl_2$ (0.2 M) Red line, 5.6 mg	52	148	180	Slightly lower	More flexible; lower degradation resistance
SB3 (Rep3)	<i>Sargassum</i> + Glycerol + $CaCl_2$ (0.2 M) Blue line, 5.5 mg	54	160	190	Higher	Highest thermal stability among bio-based samples
CP	Conventional Plastic Green line, 5.4 mg	75	180	210	High	Sharp thermal transitions; most stable

3.3 Water absorption test

The water absorption characteristics of *Sargassum*-based bioplastics show a consistent absorption-degradation pattern over 35 days of testing, demonstrating their hydrophilic nature and

biodegradability. [Figure 5](#) illustrates the water absorption characteristics of *Sargassum* bioplastics over time, indicating their initial shape and changes after 5, 10, 20 and 35 days, respectively.

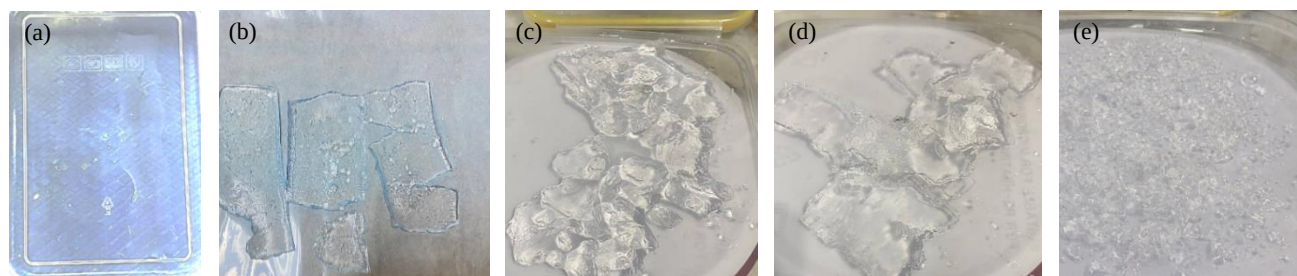


Figure 5. Water absorption characteristics (a) initial shape of *Sargassum* bioplastics; (b) SB after 5 days; (c) SB after 10 days; (d) SB after 20 days; (e) SB at 35 days

[Figure 6](#) presents the water absorption behaviour of the *Sargassum*-based bioplastic, expressed as mean $\pm$ standard deviation from triplicate measurements. The samples exhibited rapid water uptake within the first 48 h, followed by a gradual decline in measurable mass over time. The initial dry weights ranged from 0.70 g to 0.88 g across replicates. This increased sharply by Day 2, reaching a mean value of approximately 37.8 g. The relatively large standard deviation observed at this early stage reflects variability in swelling behaviour among replicates, likely due to minor differences in film thickness, porosity, and cross-link density. The pronounced hydrophilicity is consistent with previous findings on glycerol-plasticized alginate films, as

abundant hydroxyl and carboxyl functional groups promote hydrogen bonding with water molecules ([Mohammed et al., 2023](#); [Tarangini et al., 2023](#)). Following the initial swelling phase, a gradual reduction in measurable mass was observed from Day 5 onward. This decline is attributed to both the progressive structural weakening of the hydrated polymer network and the partial hydrolytic breakdown of ionic cross-links.

The decrease in mass between Day 10 and Day 30 indicates destabilization of the cross-linked alginate matrix. This is consistent with literature reporting that prolonged immersion weakens calcium-mediated ionic bridges, leading to fragmentation and

erosion of the polymer network (Vandanjon et al., 2023; Jo et al., 2024). Although ionic cross-linking enhances structural stability during early immersion, sustained hydration promotes network loosening and eventual disintegration. By Day 35, the bioplastic samples had undergone complete structural disintegration, leading fragmented gel-like residues to

disperse in the surrounding water. Consequently, quantitative mass measurement was not possible, because no intact polymer matrix could be recovered for weighing. The visual evidence of fragmentation supports previously reported aqueous degradation behaviour of alginate-based marine biopolymers (Gross and Enck, 2021).

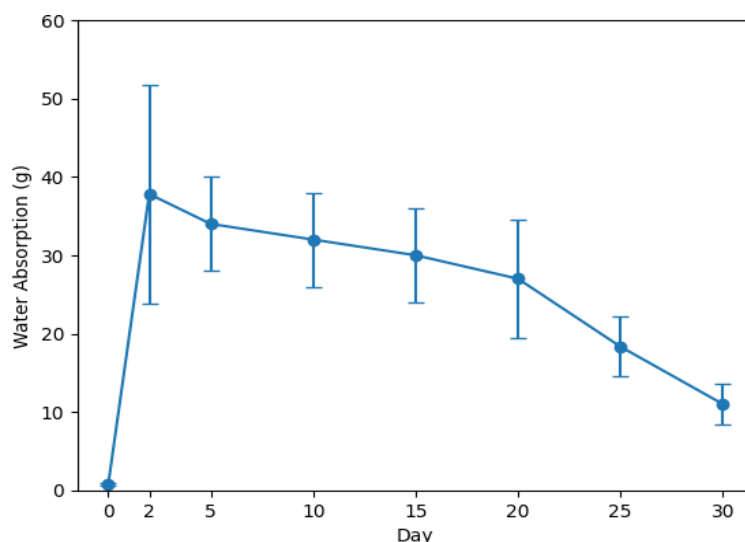


Figure 6. Water absorption of *Sargassum* bioplastic (mean $\pm$ SD) over time

The biodegradability of the *Sargassum*-based bioplastic was evaluated over 30 days under soil burial conditions, with results expressed as mean $\pm$ standard deviation from triplicate measurements (Figure 7). A progressive reduction in remaining mass was observed throughout the testing period, confirming the biodegradable nature of the material. The initial average mass of approximately 1.03 g decreased markedly within the first 7 days to around 0.53 g,

indicating rapid early-stage degradation. The relatively large standard deviation at Day 7 reflects variability in microbial activity and moisture exposure among replicates, which is typical in soil burial environments. By Day 14, the remaining mass had declined to near-zero values, suggesting the substantial structural breakdown of the polymer matrix.

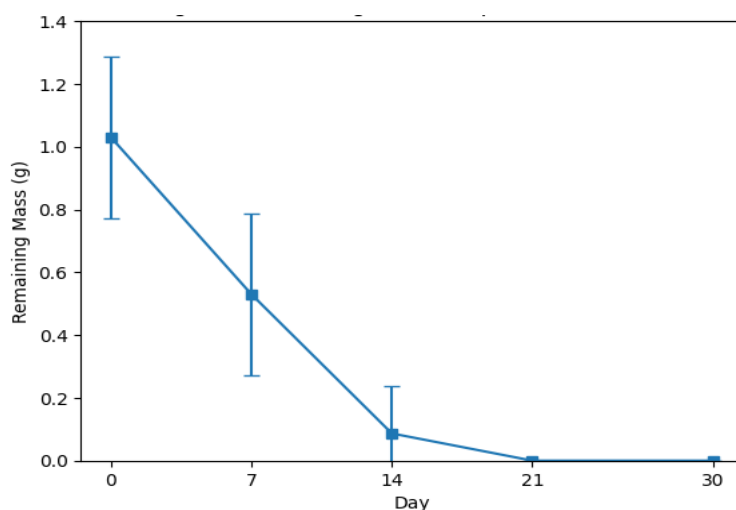


Figure 7. Biodegradation of *Sargassum* bioplastic (mean $\pm$ SD) over time

Complete degradation was observed between Day 21 and Day 30, with no recoverable material remaining by the end of the experiment. The rapid mass loss is attributed to the high content of biodegradable polysaccharides, particularly alginate and cellulose, which are susceptible to enzymatic and microbial degradation under moist soil conditions (Mohammed et al., 2023; Zdiri et al., 2022). Initial water uptake likely enhanced microbial accessibility by increasing both polymer chain mobility and surface exposure. The degradation profile observed in this study aligns with previously reported 21-40 day decomposition windows for seaweed-derived bioplastics under aerobic conditions (Abu Ubaidah et al., 2024; Akbar and Mustari, 2024; Elkaliny et al., 2024). These findings support the environmental compatibility of *Sargassum*-based bioplastics and highlight their suitability for short-term and compostable packaging applications, in which controlled and timely degradation is required.

3.4 Grease absorption test

The grease absorption test was conducted to evaluate the oil resistance of the *Sargassum*-based bioplastic under elevated temperature conditions relevant to food packaging applications. The results have been presented as mean $\pm$ standard deviation from quadruplicate measurements (Figure 8).

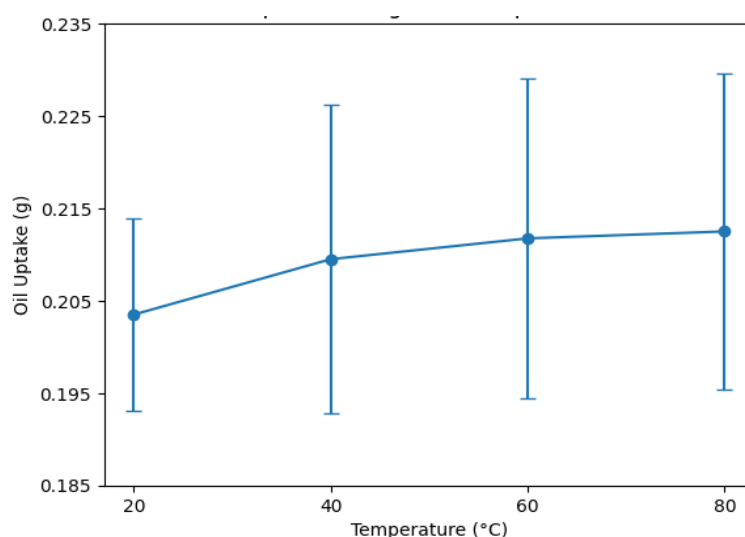


Figure 8. Grease absorption test

4. CONCLUSION

This study evaluated the feasibility of utilizing *Sargassum* seaweed as a renewable feedstock for

A gradual increase in oil uptake was observed as temperature increased from 20°C to 80°C. The mean weight rose slightly from approximately 0.20 g at 20°C to around 0.21-0.22 g at higher temperatures. This trend indicates temperature-dependent diffusion behaviour, as an elevated temperature reduces oil viscosity and enhances polymer chain mobility, facilitating greater oil penetration into the biopolymer matrix.

The relatively wide-ranging standard deviations observed at higher temperatures suggest variability in oil diffusion among replicates, likely influenced by minor differences in film thickness, surface morphology, and cross-link density. Despite the observed increase, the overall magnitude of oil uptake remained moderate, indicating that the calcium-cross-linked alginate network provides partial resistance to non-polar diffusion.

These findings are consistent with previous reports on alginate- and cellulose-based films, which have demonstrated moderate oil barrier properties with increased permeability at elevated temperatures (Mohammed et al., 2023; Tarangini et al., 2023). Although grease resistance is not absolute, the performance observed suggests suitability for short-term packaging of warm or moderately oily foods. Further optimization, such as surface coating or multilayer barrier integration, may enhance oil resistance for use in demanding applications.

biodegradable bioplastic production, with specific emphasis on packaging applications. The incorporation of glycerol as a plasticizer and calcium chloride as an ionic cross-linker contributed to the

improvement of mechanical performance, yielding films with enhanced tensile strength and flexibility compared to the conventional plastic reference. These results indicate suitability for low-load, short-term packaging applications.

Thermal analysis revealed a glass transition temperature of approximately 54°C, a melting temperature near 160°C, and a degradation onset around 190°C, confirming moderate thermal stability appropriate for handling and typical environmental exposure conditions. Water absorption tests demonstrated rapid initial swelling followed by progressive structural weakening under prolonged immersion, reflecting the hydrophilic nature of the alginate-based matrix. Grease absorption further exhibited a modest temperature-dependent increase, with overall oil uptake remaining moderate even at elevated temperatures. These behaviours together suggest that while the material may not be fully impermeable to moisture or oils, it maintains acceptable barrier performance for short-term contact with dry or moderately greasy foods. Biodegradation analysis confirmed substantial mass reduction within the first two weeks, with complete structural disintegration within 21-30 days under soil burial conditions. Such a controlled and timely degradation highlights the environmental compatibility of the material and its advantage over persistent petroleum-based plastics.

In conclusion, the functional performance of the *Sargassum*-based bioplastic is governed by a balance between hydrophilic diffusion mechanisms and calcium-mediated ionic network stabilization. *Sargassum*-derived bioplastics show strong potential as sustainable alternatives for compostable and single-use packaging applications.

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AUTHOR CONTRIBUTIONS

Conceptualization, Dzulaikha Khairuddin; Methodology, Nur Syazwina Kamarozaman and Nasaei Zainuddin; Validation, Dzulaikha Khairuddin and Nur

Syazwina Kamarozaman; Formal Analysis, Dzulaikha Khairuddin; Investigation, Nur Syazwina Kamarozaman; Resources, Dzulaikha Khairuddin and Nasaei Zainuddin; Data Curation, Nur Syazwina Kamarozaman; Writing-Original Draft Preparation, Nur Syazwina Kamarozaman; Writing-Review and Editing, Dzulaikha Khairuddin; Visualization, Nur Syazwina Kamarozaman; Supervision, Dzulaikha Khairuddin; Project Administration, Dzulaikha Khairuddin; Funding Acquisition, Dzulaikha Khairuddin.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no competing interests to disclose

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An Appraisal of Green Gross Provincial Product of a Tourist Island - An Analysis Focusing on Phuket

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ABSTRACT

This study incorporated provincial input-output tables into the environmental assessment process for Phuket - an island with an economy based largely on tourism. The life cycle assessment approach was employed considering five impact categories including climate change, fossil scarcity, water, eutrophication and land use for green gross provincial product (GGPP) calculation. Degradation cost and depletion cost originating from global warming and fossil resource scarcity were the main contributors. The results indicated that for a tourism-based economy such as Phuket, industries associated with tourism, such as accommodation and food service activities, wholesale and retail trade and repair of motor vehicles, as well as transportation and storage are highly profitable, but also impose heavier environmental burdens compared to other sectors. The sectoral GGPP of electricity, gas, steam, and air conditioning supply, as well as water supply, sewerage, waste management and remediation activities, involved more in local residents' living, accounted for 25% and 50% of the sectoral gross provincial product (GPP), respectively. In 2015, Phuket GGPP was 160 billion THB, corresponding to 96% of the Phuket GPP. As Phuket relies heavily on its beautiful environment to bring economic value, it is imperative to protect it against environmental damages especially irrecoverable ones.

HIGHLIGHTS

This study applies provincial input-output (IO) tables developed for assessment of a tourism-based economy to reveal the study area's environmental costs and green gross provincial product (GGPP).

1. INTRODUCTION

In an attempt to preserve and safeguard natural resources and environment for long-term human well-being, sustainable development has emerged as a significant issue over the past decades. It emphasizes the balance between economic growth and environmental preservation to maintain the environmental vitality. To progress along this path, there is ongoing effort to propose and formulate appropriate indicators for measuring growth (Adewumi et al., 2023).

As a common indicator of economic development, gross domestic product (GDP) is typically used to represent the growth of a national economy over a specific period. While useful in measuring economic development, concerns have been raised that GDP does not accurately reflect the well-being of a national economy (Schweinfest et al., n.d). One of the most frequent criticisms of GDP is that it totally omits the environment, or rather, counts the environmentally harmful activities as economic output (Chan et al., 2022). For instance, forest-based industries

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could foster GDP growth (Li et al., 2019), but could negatively influence well-being and economic development since it causes deforestation. As an effort to include environmental damage into economic growth assessment, green gross domestic product (GGDP) has been proposed as an indicator to measure the growth of a national economy under the context of sustainable development (Wei et al., 2020). GGDP is defined as the difference of traditional GDP and the costs from environmental deterioration and resources depletion (Wu and Han, 2020). Further efforts have been made to implement this indicator on regional (Yang and Poon, 2009) or provincial (Qi et al., 2021; Cai and Hu, 2024) scales, revealing disparities in environmental damage for different economic structures.

Over the course of the past 60 years, tourism has continually developed and significantly contributed to the growth of the global economy (Greco et al., 2017). According to the World Travel and Tourism Council, before COVID in 2019, travel and tourism generated 9.17 trillion USD, representing 10.4% of the global gross domestic product (GDP). About 10% of employment opportunity worldwide came from this industry (World Travel and Tourism Council, 2021a). Despite the intense vulnerability to environmental, political, and socio-economic variations, tourism has resiliently overcome countless challenges and obstacles (Novelli et al., 2018). Even after the occurrence of the destructive pandemic COVID 19, which caused a substantial reduction in travel and tourism's income to 4.78 trillion USD in 2020, it achieved a rapid recovery. In 2021, this industry contributed 5.81 trillion USD, equivalent to 6.1% of the global economy, experiencing a vast increase of 21.7% compared to the industry's income in the previous year (World Travel and Tourism Council, 2021b).

Besides the substantive economic gains, there are also several damaging environmental consequences as a result of tourism development (Zhong et al., 2011). Infrastructure construction, energy and resource consumption, and pollution and waste from tourist activities have resulted in serious adverse environmental and ecological damages (Davenport and Davenport, 2006). Tourism is one of the most significant consumers of energy. An increase in tourist activities could result in a rise in energy consumption from transportation, food services, accommodation, and other tourism operation processes (Acaroglu et al., 2023). Furthermore, tourism also accounted for 11% of the greenhouse gas (GHG) emissions worldwide (World Travel and

Tourism Council, 2021a). Other effects such as deforestation (Chakraborty and Ghosal, 2024) and water pollution (Bi and Li, 2024) are additional environmental issues that could arise directly or indirectly as a result of tourism. Poor management could intensify those damages (Sunlu, 2003). Given the worldwide concern to alleviate serious damage series caused by tourism, more effort is demanded for information on the environmental burdens caused by tourism which is an important step in the mitigation process (Li et al., 2023).

There are several methods that are widely applied to assess environmental impacts such as green performance map, environmental value stream map, life cycle assessment (LCA) (Shahbazi et al., 2019), material flow analysis (Xu et al., 2024), and cumulative effects assessment (Greaves and Parrott, 2024). From a variety of approaches, LCA is commonly regarded as one of the most suitable and encompassing approaches to assess environmental burden through transparent evaluation procedures and in-depth analysis (Curran et al., 2017). The combination of LCA and input-output (IO) tables can enable the measurement of environmental burdens caused by both industries and from final demand (Liang et al., 2024), including governments and residents' activities.

As an effective tool providing information on the interrelationships between the inputs and outputs of industries (Markaki and Papadakis, 2024), the application of LCA and input-output tables can offer insights into how economic sectors should be modified since the input-output tables provide information on the connections between different industries, producers, and purchasers. For instance, if there is a requirement to reduce agricultural production, this method could forecast the potential impacts of this reduction in the related sectors, such as manufacturing (Miller and Blair, 2009). Therefore, it is applied as the main method to assess environmental impacts in this study.

Building on this framework, most IO-LCA applications have been conducted at the national level, where comprehensive input-output tables and environmental extensions are readily available, such as in Thailand (Kunanuntakij et al., 2017), China (Wang et al., 2020), and Brazil (Brito et al., 2025). At the provincial level, existing studies are often based on officially available regional input-output tables, as in the cases of Guizhou Province (Yi et al., 2020) and Shenyang City (Chen et al., 2020), while the construction of fully survey-based provincial input-

output tables remains highly data-intensive and is frequently constrained by limited availability of regional statistics. In this context, this research contributes to the literature by taking an initial step toward applying IO-LCA at the provincial scale through the use of a localization technique to adapt national input-output data to provincial conditions. Rather than aiming to construct a complete provincial input-output table for Phuket, the study demonstrates how a non-survey regionalization approach can be employed to approximate provincial inter-industry relationships under conditions of data scarcity. This methodological contribution provides a practical and transferable starting point for green gross provincial product (GGPP) assessment in data-constrained tourism-oriented provinces.

This study aims to demonstrate an evaluation of GGPP applying input-output analysis of Phuket, a tourist island in the southern part of Thailand. GGPP is an indicator developed on the same conceptual basis as GDP, but it is utilized to reflect the negative externalities associated with the final goods and services of a province. Phuket is selected as the study area due to its 11th rank among the leading tourist destinations worldwide in 2017 (CNN, 2017). According to a study conducted by C9 Hotelworks organization, hotels and restaurants, a major component of tourism, contributed 35% of Phuket's gross provincial product (GPP) (C9 Hotelworks, 2015) manifesting the important role played by tourism in the economic growth of this province. Before COVID 19, from 2014 to 2018, Phuket

attracted an average of 13.1-13.4 million tourists annually (Maswongssa, 2020). It is administratively divided into 17 sub-districts as presented in Figure 1.

The outcomes of this study are the illustration of Phuket's environmental perspective in terms of numerical value and revealing Phuket's industries mostly responsible for environmental burdens, thus being able to provide recommendations for regulation with the aim of improvement. Furthermore, this study could also serve as a model for other tourist destinations to incorporate environmental burdens into their economic accounting by applying input-output analysis. This framework could also facilitate the acquisition of additional data while shaping policies for a specific area.

2. METHODOLOGY

2.1 Materials

There are two main categories of data in this paper: national input-output tables, which record the flows of goods and services between suppliers and consumers within Thailand; and activity data of fuel consumption, electricity consumption, food consumption, water use, waste disposal, and land use. The data was mainly obtained from governmental organizations as presented in Table 1.

The economic sectors were categorized according to the standard system comprising 19 sectors established by NESDC. To enhance readability and comprehension, abbreviated names for these sectors are created as shown in Table 2.

Table 1. Sources of information used in this study

Data	Sources
Energy	Energy Policy and Planning Office (EPPO) National Statistical Office of Thailand (NSO)
Land use	Land Development Department (LDD)
Waste	Provincial Office of Natural Resources and Environment Phuket
Water	Provincial Water Authority (PWA) National Statistical Office of Thailand (NSO)
Wastewater	Regional Environment Office 15 (EPO)
Thailand input-output tables	Office of the National Economic and Social Development Council (NESDC)

Table 2. Economic sector names presented in the paper

NESDC system	Abbreviated names
Agriculture, forestry, and fishing	Agriculture
Mining and quarrying	Mining and Quarrying
Manufacturing	Manufacturing
Electricity, gas, steam and air conditioning supply	Energy Supply

Table 2. Economic sector names presented in the paper (cont.)

NESDC system	Abbreviated names
Water supply; sewerage, waste management and remediation activities	Water Supply and Cleaning Activities
Construction	Construction
Wholesale and retail trade and repair of motor vehicles	Trade Activities
Transportation and storage	Transportation and Storage
Accommodation and food service activities	Accommodation and Food Service
Information and communication	Information and Communication
Financial and insurance activities	Finance and Insurance
Real estate activities	Real Estate
Professional, scientific, and technical activities	Research
Administrative and support service activities	Administrative Activities
Public administration and defense; compulsory social security	Public Administration and Social Security
Education	Education
Human health activities	Human Health
Arts, entertainment, and recreation activities	Arts, Entertainment, and Recreation
Other service activities	Other Activities

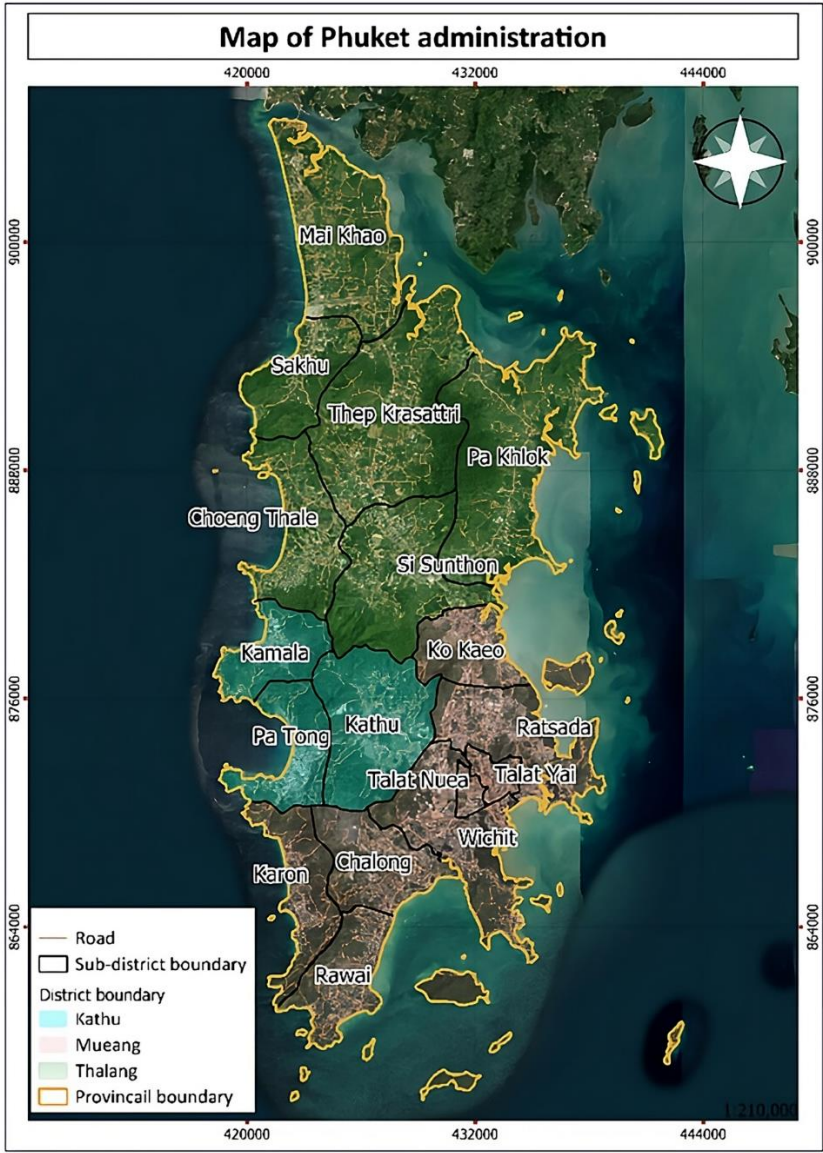


Figure 1. Study area - Phuket

2.2 Methods

2.2.1 Environmental input-output assessment

1) National input-output table analysis

Input-output table or the basic Leontief input-output model is normally created from economic statistical data of an identified region such as a nation, a state, or province. Input-output tables show the basic information of the production flows of each industry. There are two ways to consume products of industry. First, products go into the manufacturing processes of other industries. Second, products go into customer's consumption. Input-output tables represent the number of products from an industry (considered as a

producer) that go into other industries (considered as consumers) and to customers (final demand). The rows in value added account for non-industrial input, such as labor, needed to create products. Therefore, in general, the column shows the required input of each sector in order to produce the output of an industry. The row describes the distribution of an industry's products to other industries and customers.

The sum of sectoral value added equals to the sum of sectoral final demand. Each of them is equal to the gross domestic product of a country or gross provincial product of a province. In technical form, input-output tables are written as shown in Table 3.

Table 3. The standardized form of input-output tables

Industry		Buying sector (i)				Final demand	Total output
		1	2	...	n		
Selling sector (j)	1	z_{11}	z_{12}	...	z_{1n}	f_1	X_1
	2	z_{21}	z_{22}	...	z_{2n}	f_2	X_2
	...	...	...	...	...	...	...
	n	z_{n1}	z_{n2}	...	z_{nn}	f_n	X_n
Payment sector	Value added	v_1	v_2	...	v_n		
Total output		X_1	X_2	...	X_n		

x_i is the total amount of product i

f_i is the final demand for product i

z_{ij} is the intermediate consumption of product i required by sector j

The basic equation can be written as:

$$X_1 = z_{11} + z_{12} + \dots + z_{1n} + f_1 = \sum_{j=1}^n z_{1j} + f_1 \quad (1)$$

For every sector:

$$\begin{aligned} X_1 &= z_{11} + z_{12} + \dots + z_{1n} + f_1 \dots \\ X_i &= z_{i1} + z_{i2} + \dots + z_{in} + f_i \dots \\ X_n &= z_{n1} + z_{n2} + \dots + z_{nn} + f_n \dots \end{aligned}$$

or

$$X = \begin{pmatrix} x_1 \\ \dots \\ x_n \end{pmatrix} \quad Z = \begin{pmatrix} z_{11} & \dots & z_{1n} \\ \dots & \dots & \dots \\ z_{n1} & \dots & z_{nn} \end{pmatrix} \quad F = \begin{pmatrix} f_1 \\ \dots \\ f_n \end{pmatrix}$$

and

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots \\ a_{n1} & \dots & a_{nn} \end{pmatrix}$$

In the matrix form, it can be written as:

$$\begin{aligned} x_i &= \sum_{j=1}^n z_{ij} + f_i = \sum_{j=1}^n a_{ij} x_j + f_i \\ \Leftrightarrow X &= (A \times X) + F \\ \Leftrightarrow X \times (I - A) &= F \\ \Leftrightarrow X &= (I - A)^{-1} \times F \end{aligned}$$

In the first step, the industrial coefficient matrix A of Thailand was calculated using information from governmental sources. It should be noted that A represents the industrial coefficient matrix of Thailand, I is an identity matrix, X is a matrix of total output of Thailand, and F is matrix of final demand.

The supplementary file contains the details of calculation results. The code system outlined in Table A1 is used to represent all sectors in this file. The results of Thailand industrial coefficient matrix A are presented in Table A2.

2) Provincial input-output tables

Given the variation between national and regional economy, specific input-output tables have been considered for smaller geographic scales. Regions, provinces, or other geographic scales might have less resources for data collection related to input-output tables construction. Less effort is involved in estimating regional input-output tables from the national input-output tables than surveying information to create region-specific input-output tables (Miller and Blair, 2009). There are several techniques to convert regional input-output tables from national ones. One of the most common methods

is using location quotients (Kowalewski, 2015) which uses primary conversion factors to adjust corresponding national coefficients to obtain regional coefficients. The application of techniques depends on the available data that regions or provinces have. This method is considered time and budget saving to construct provincial input-output tables (Flegg et al., 2021) and is useful for policy makers or government officers.

This study constructed the provincial input-output tables from Thailand's national input-output tables as shown step by step in Figure 2. The 180 sectors of the Thailand input-output tables were reorganized into 19 sectors in accordance with the Thailand Standard Industrial Classification 2009 (TSIC-2009) (Department of Employment, 2009). This reorganization was carried out using the conversion quotient from national input-output tables to provincial input-output tables calculated based on sectoral GDP of Phuket.

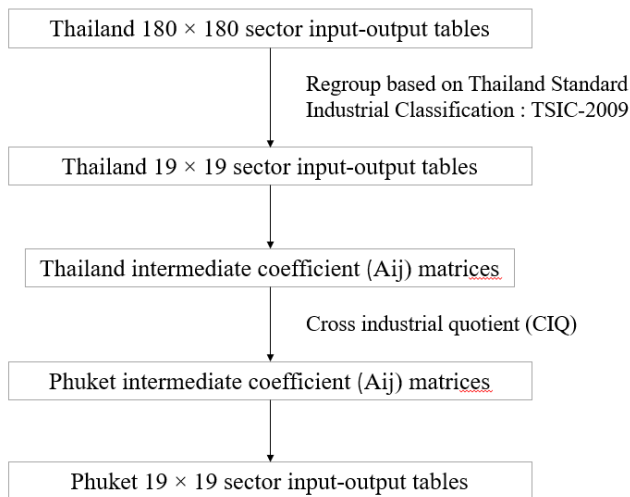


Figure 2. Process of provincial input-output tables construction

Then, the cross industrial quotation was applied to calculate the Phuket co-efficient matrix. Conversion factor from national input-output tables to provincial input-output tables, called Cross Industry Quotient (CIQ), was obtained by using Equation 2 (Miller and Blair, 2009):

$$CIQ_{ij}^{PK} = \left(\frac{\frac{x_i^{PK}/x_i^{TH}}{x_j^{PK}/x_j^{TH}}}{\frac{x_j^{PK}/x_j^{TH}}{x_j^{PK}/x_j^{TH}}} \right) = \left(\frac{\frac{x_i^{PK}/x_i^{TH}}{x_j^{PK}/x_j^{TH}}}{\frac{x_j^{PK}/x_j^{TH}}{x_j^{PK}/x_j^{TH}}} \right) = \left(\frac{\frac{x_i^{PK}/x_i^{TH}}{x_j^{PK}/x_j^{TH}}}{\frac{x_j^{PK}/x_j^{TH}}{x_j^{PK}/x_j^{TH}}} \right) \quad (2)$$

Where: x_i^{PK} is the sum of product i in Phuket; x_i^{TH} is the sum of product i in Thailand; x_j^{PK} is the gross output of sector j in Phuket; x_j^{TH} is the gross output of sector j in Thailand; x^{PK} is the gross output of Phuket; x^{TH} is the gross output of Thailand; f_i^{PK} is the final demand for product i in Phuket; f_i^{TH} is the final demand for product i in Thailand; f_j^{PK} is the final demand for sector j in Phuket; f_j^{TH} is the final demand for sector j in Thailand.

The coefficient matrix of Phuket was then calculated using the Equation 3:

$$a_{ij}^{rr} = \begin{cases} (CIQ_{ij}^{PK})^{TH} a_{ij}^{TH} & \text{if } CIQ_{ij}^{PK} < 1 \\ a_{ij}^{TH} & \text{if } CIQ_{ij}^{PK} \geq 1 \end{cases} \quad (3)$$

Where: a_{ij}^{rr} the interindustry coefficient of Phuket; CIQ_{ij}^{PK} the cross industrial quotient of Phuket; a_{ij}^{TH} the interindustry coefficient of Thailand.

The interpretation of CIQ is that if the product i in Phuket relative to the product i in Thailand is larger than the output of sector j in Phuket relative to the output of the sector j in Thailand ($CIQ_{ij}^{PK} \geq 1$), the product i is sufficient for the sector j 's needs within Phuket. In contrast, if the product i in Phuket relative to the product i in Thailand is smaller than the output of sector j in Phuket relative to the output of sector j in Thailand, the product i is insufficient for the sector j 's needs within Phuket; then the needs of product i for the sector j is imported and coefficient a_{ij}^{rr} is downscaled by $CIQ_{ij}^{PK}(a_{ij}^{TH})$ if $CIQ_{ij}^{PK} < 1$. The CIQ of this study is presented in the Table A3 in the supplementary data.

There are several techniques introduced to convert regional input-output tables from national one. Those techniques use primary conversion factors to adjust corresponding national coefficients to obtain regional coefficients. The application of techniques depends on different available data that regions or provinces have. This method is considered time and budget saving to construct provincial input-output tables (Flegg et al., 2021). Among those approaches, location quotients is considered as one of the most common methods used in regionalizing input-output tables (Kowalewski, 2015; Pominova et al., 2022). The first introduced location quotient was Simple Location Quotient (SLQ). However, this technique

overlooks the impacts of the demanding sector. One of the initial enhancements of the SLQ was the cross-industry quotient (CIQ) (Kowalewski, 2015). This technique considers both the effects of supplying sectors and demanding sectors (Okamoto, 2014). While there are numerous studies on SLQ and CIQ, there are very limited studies on Supply-Demand Pool Approaches, Fabrication Effects, or Regional Purchase Coefficients. The choice of the best regionalization method often hinges on the quality and availability of data, as different methods have varying data requirements. Supply-Demand Pool Approaches regionalize national input-output tables using national supply and use tables rather than national input-output tables as a reference (Piispala, 2000). As a result, this method requires different data sets than those employed in this study. Several studies highlight that Regional Purchase Coefficients are often considered the most unreliable component of non-survey approaches (Lazarus et al., 2002). Furthermore, CIQ stands out for its advantages of adaptability as a non-survey method. It could be used for different regions with various economic context under the condition of limited data availability. As it does not require data-intensive collection, it is also considered as a resource-saving method (Flegg et al., 2021). Although it cannot be competed to precision of more data-intensive techniques, its feasibility makes it practical tool for regional economic analysis, particularly in the contexts with limited resources.

After matrix A of Phuket (Table A4 in the supplementary data) was obtained, the next step was the calculation of the inverse matrix $(I - A)^{-1}$ and $X = (I - A)^{-1} \times F$ (Note that: I is identity matrix).

The conversion factor, calculated using CIQ technique, can be applied when data on the final demand (or GDP) of each economic component is available. Therefore, this study employed the CIQ technique to convert Thailand input-output tables to Phuket input-output tables.

2.2.2 Environmental burden assessment

ReCiPe 2016 - a life cycle impact assessment method at the midpoint and endpoint levels was employed to evaluate the environmental burdens caused by human activities in Phuket. ReCiPe 2016 is a multi-impact LCIA method and is among the most comprehensive frameworks available for environmental impact assessment. It quantifies impacts at the midpoint level across 18 categories, which can be further aggregated into endpoint damage

categories— human health, ecosystem quality, and resource availability—and, if required, into a single weighted score (Cespi et al., 2025). The impact assessment process is illustrated in Figure 3.

Across numerous studies throughout years, tourism has been recognized as one of the significant contributors to energy consumption (Shan and Ren, 2023) and GHG emissions (Gössling et al., 2023). As an island having tourism as a major economic driver, Phuket is expected to exhibit significant figures on fuel consumption and GHG emissions. Solid waste (Hayati et al., 2020) wastewater (Wells et al., 2016), and land use change (Iversen et al., 2024) are also acknowledged as major issues in a tourist island requiring suitable management. As Phuket has been experiencing water shortage frequently (Sattraburut et al., 2024), water use category was also included in this study. There is no notable sign of particulate matter pollution detected on this island (Kumlom, 2021); hence, it is not included in this study. Since mining - the main source of heavy metal has been closed since 1992 (Akkajit et al., 2018) and tourism is a relatively insignificant source of contamination compared to past mining operations, (Akkajit et al., 2018; Puttiwongrak et al., 2019), this category is also excluded. Therefore, five impact categories were assessed in this study, including global warming, fossil resource scarcity, water use, eutrophication, and land cover loss. With the ultimate goal of evaluating GGPP of Phuket, two global impact categories-global warming and fossil resource scarcity were assessed based on consumption-based approach, while local impacts were assessed based on production-based approach, focusing only on factors directly affecting and caused by this island.

The impact assessment was done using the Equation 4:

$$\text{Emissions/pollutant} = \text{Activity data} \times \text{Emission/pollution factor} \quad (4)$$

The national input-output tables record the intersectoral flows between industries in a given period, usually a year. Initially, the researchers considered the data at country level, for which the economic activities are categorized into different sectors. The data captures the monetary values associated with the production and distribution of an industry at national level. On the other hand, at the provincial level, there are cases that goods are imported from outside. In this case, the data focuses

on the monetary values related to the distribution of products of an industry. In this context, the data from input-output tables can be effectively utilized to allocate the resource consumption or calculate environmental emissions/pollutants when integrated with the statistical data. In this study, it was used for

the environmental burden allocations in global warming, fossil resource scarcity, water use, and eutrophication. Together with statistical data from government sources, it provides a holistic impact assessment for a tourist island such as Phuket.

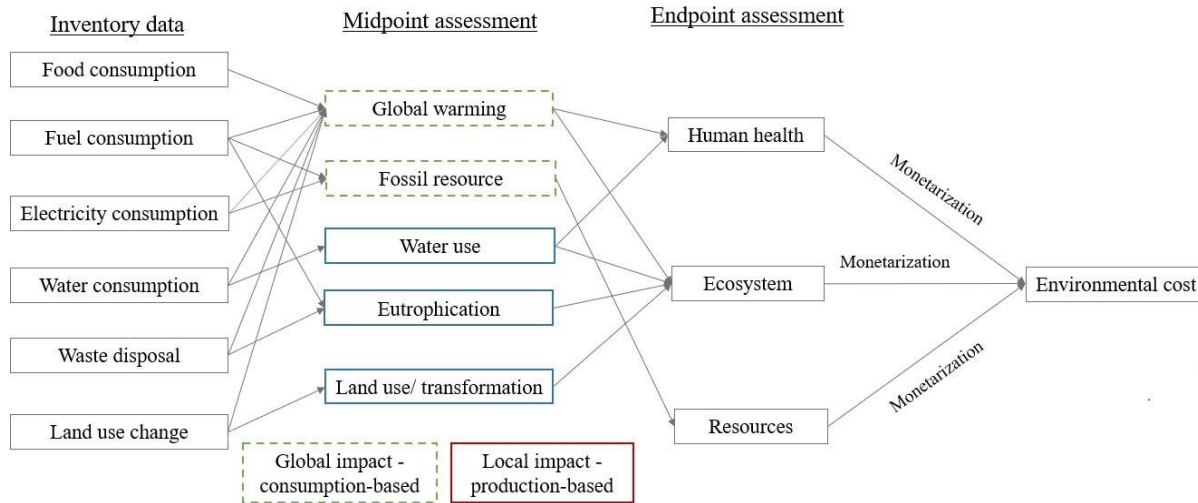


Figure 3. Impact assessment process of this study

2.2.3 Environmental cost assessment

After the step of environmental impact assessment, monetization process was applied to calculate the environmental costs. The monetization factors were obtained from the previous study (Kaenchan and Gheewala, 2017) which offers factors estimated based on Thailand conditions.

This paper utilized the Thailand input-output tables for the year 2015, which offer the most updated data. It serves as an example of applying input-output analysis in yearly accounting and highlights the benefits it provides.

Concerning the instabilities in monetary values across different years, all amounts were standardized to a single year 2015 using the Equation 5:

$$\text{Value}_{\text{TH}_t^*} = \text{Value}_{\text{TH}_t} \times (1+r)^{(t^*-t)} \quad (5)$$

Where; $\text{Value}_{\text{TH}_t^*}$ represents the monetization factors of Thailand in 2015, t is the year of currency accounted in valuation, t^* is the base year of calculation (2015), $\text{Value}_{\text{TH}_t}$ represents the monetization factors that needed to convert, r is the average inflation rate of Thailand over accounted period, acquired from World Bank (World Bank, 2024). In this study, r is the average inflation rate of Thailand in from 2011 to 2015.

The degradation cost is calculated using Equation 6:

$$\text{Degradation cost} = \text{Total emissions/pollutants} \times \text{environmental cost per unit} \quad (6)$$

The depletion cost is calculated using Equation 7:

$$\text{Depletion cost} = \text{Total amount of resources consumed} \times \text{environmental cost per unit} \quad (7)$$

2.2.4 Green gross provincial product calculation

According to the System of Environmental-Economic Accounting (SEEA), environmental costs comprise of degradation cost, depletion cost, and defensive cost. Degradation cost refers to the potential monetary loss as a result of damage arising from deterioration of human health and ecosystem. Depletion cost represents the expense associated with the raw material and resources extraction from the stocks, considering the return to the natural condition. Defensive cost is the expenditure involved in environmental protection and prevention (Kunanuntakij et al., 2017). The final GGPP is calculated using Equation 8:

$$\begin{aligned} \text{GGPP} &= \text{Traditional GPP} - \text{environmental costs} \quad (8) \\ &= \text{Traditional GPP} - (\text{degradation cost} + \\ &\quad \text{depletion cost} + \text{defensive cost}) \end{aligned}$$

The life cycle environmental burdens caused by global impacts were included in the GGPP calculation. While for local impacts, only the direct impact was included.

3. RESULTS AND DISCUSSION

3.1 The application of provincial Phuket input-output analysis to environmental assessment

3.1.1 Global impact assessment

The total GHG emission of Phuket in 2015 was 3,317.6 kt CO₂ equivalent, excluding emissions from Land Use, Land-Use Change and Forestry (LULUCF). It accounted for 0.8% of Thailand's GHG emissions. The contribution of LULUCF was 68.1 kt CO₂ equivalent. The largest emission contributor to global warming was electricity consumption, as presented in Figure 4, with approximately 1,455.2 kt CO₂ equivalent. Fuel consumption occupied the second biggest portion with 1,100.6 kt CO₂ equivalent. At the third place was food consumption with 502.1 kt CO₂ equivalent. The two insignificant emission sources were water consumption and wastewater contributing 11.1 and 2.1 kt CO₂ equivalent, respectively.

In terms of economic sectors-related GHG emissions, as presented in Figure 5, Energy Supply occupied the largest share, contributing approximately 1,085.8 kt CO₂ equivalent. Accommodation and Food Service accounted for the second largest proportion, contributing roughly 296.4 kt CO₂ equivalent. The

third place was Transportation and Storage with 275.4 kt CO₂ equivalent. The Water supply and Cleaning Activities hold the fourth-largest share, totaling almost 222.7 kt CO₂ equivalent, followed by Trade Activities with 166.8 kt CO₂ equivalent.

Given that Phuket is a tourist island, it is not surprising that sectors closely relevant to tourism activities, such as Accommodation and Food Service activities, Transportation and Storage, as well as Trade Activities, contributed significantly to the provincial GHG emissions. Also, sectors catering for residential daily living, such as (i) Energy Supply, as well as (ii) Water Supply and Cleaning Activities claimed even higher positions. Despite the number of tourists in Phuket during 2015 being significantly higher (around four times more) than the local population, the GHG emissions related to tourists remained approximately three times lower compared to that of the local population. This is due to the transient nature of tourists, who typically stay on the island for only short periods and do not reside there year-round like the residents. If adjusted to the same basis, converting number of tourists to residents staying on this island for the whole year, the number of tourists was significantly lower than the resident population. In addition, Phuket also has nearly 200,000 people who are not registered in the household system. This was also highlighted by the data provided by Thailand Greenhouse Gas Management Organization (TGO). It shows that when compared on the same basis, the number of tourists were 4.4 times less than the number of Phuket residents (TGO, 2013).

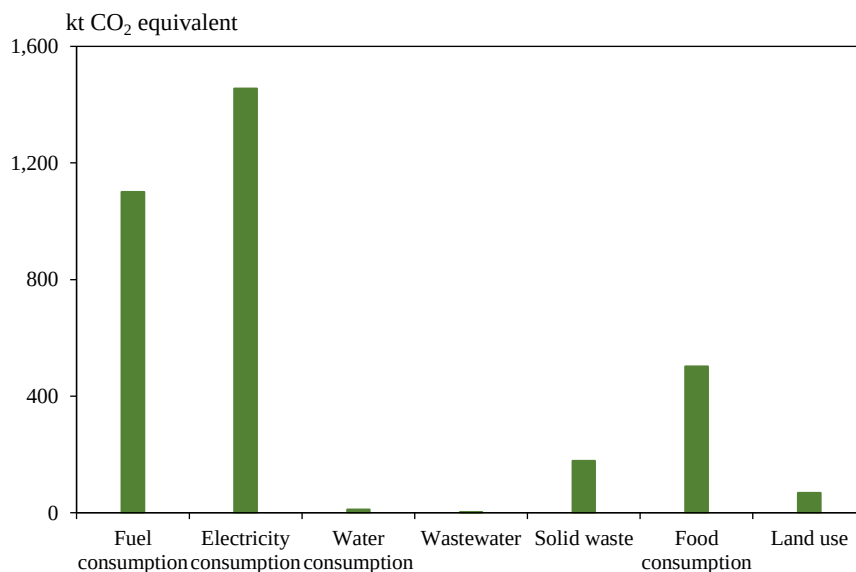


Figure 4. Global warming potential sources in Phuket

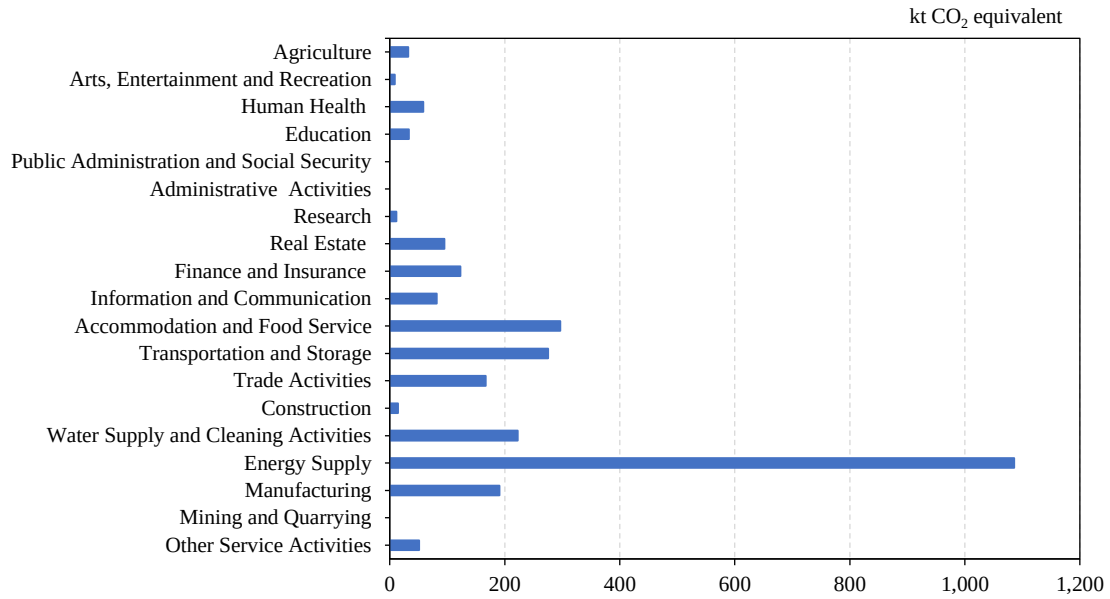


Figure 5. Global warming potential by economic sectors in Phuket in 2015

On the other hand, these figures also provide an example of a substantial disparity between national and provincial assessment results concerning various economic core sectors. At the national level, manufacturing and agriculture, two significant economic sectors, contributing 27% and 9% to the national GDP, also were significant emission sources, contributing 60% and 22% to the national GHG emissions, accordingly (Kunanuntakij et al., 2017). However, at the provincial level, these two sectors were comparatively insignificant, accounting for merely 9% and 1% of Phuket's overall GHG emissions, respectively, which corresponds to a contribution of 2% and 3% to the Phuket's GPP. This

aligns with the reality that Phuket relies heavily on tourism as its main source of income, directly contributing 41% to Phuket's GPP and production industries are not highly developed there.

In 2015, Phuket's overall fuel consumption amounted to 581.7 kt of oil equivalent. As illustrated in Figure 6, Energy Supply still held the most substantial share, accounting for 291.2 kt oil equivalent. Being the second largest consumer, Transportation and Storage accounted for 74.8 kt oil equivalent. Accommodation and Food Service claimed the third biggest share with 50 kt oil equivalent, higher than the next one which was Manufacturing at 47.5 kt oil equivalent.

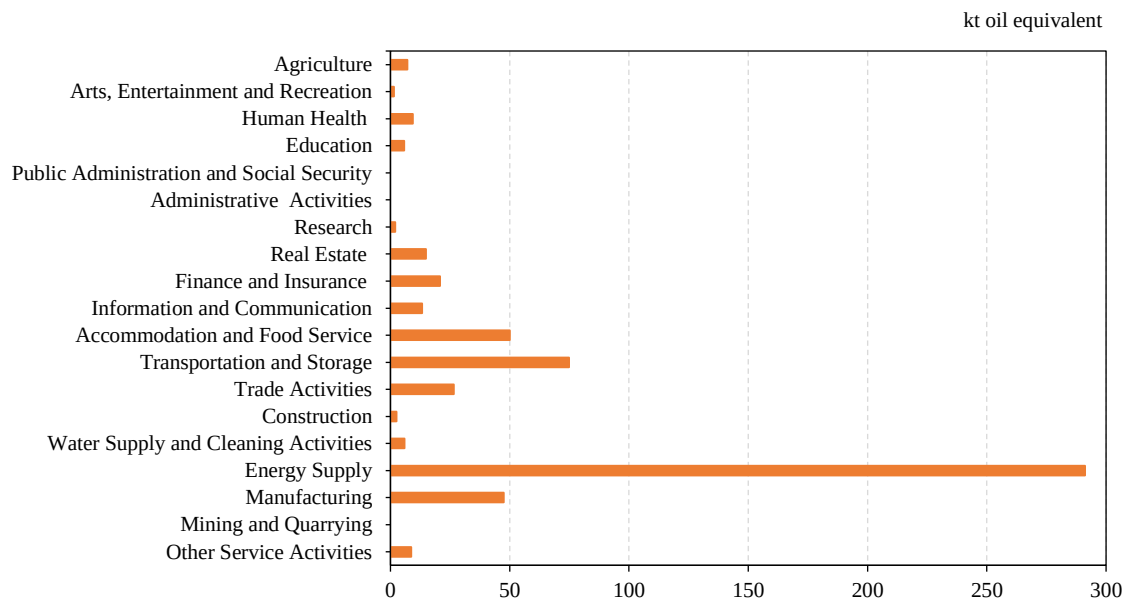


Figure 6. Fuel consumption by economic sectors in Phuket in 2015

As presented in Figure 7, the most consumed types of fuel in Phuket in 2015 were natural gas with 184.4 kt oil equivalent. Next was diesel with 152.2 kt oil equivalent. It was closely followed by gasohol, accounting for 138 kt oil equivalent. Coal and lignite occupied the fourth largest share, with 40.3 kt oil equivalent.

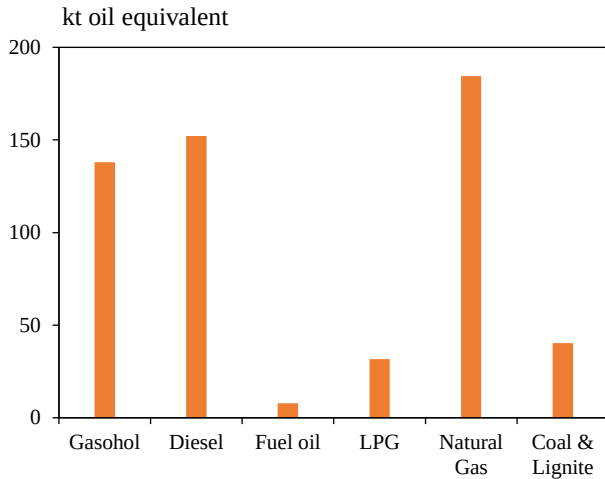


Figure 7. Fossil consumption by types in Phuket in 2015

3.1.2 Local impact assessment

Water use represents an important local environmental impact, reflecting the pressures of economic activities on regional water resources. Previous research has demonstrated that assessment based on regional input-output tables for a single province provided lower figures compared to the statistical data (Long et al., 2020). In this study, Phuket, a province with three main water supply sources - including Provincial Waterwork Authority, private sector and groundwater, poses the possibility of exacerbating this issue, as one source, such as groundwater, may not be recorded in economic transactions. The input-output assessment indicates that provincial water consumption was about 15 million m³, which was 24.8% lower than the water consumption figure provided by the Provincial Waterworks Authority. Hence, this study proposes combining government statistics with the input-output analysis to evaluate environmental impacts associated with economic activities at the provincial level, thereby avoiding potential underestimation.

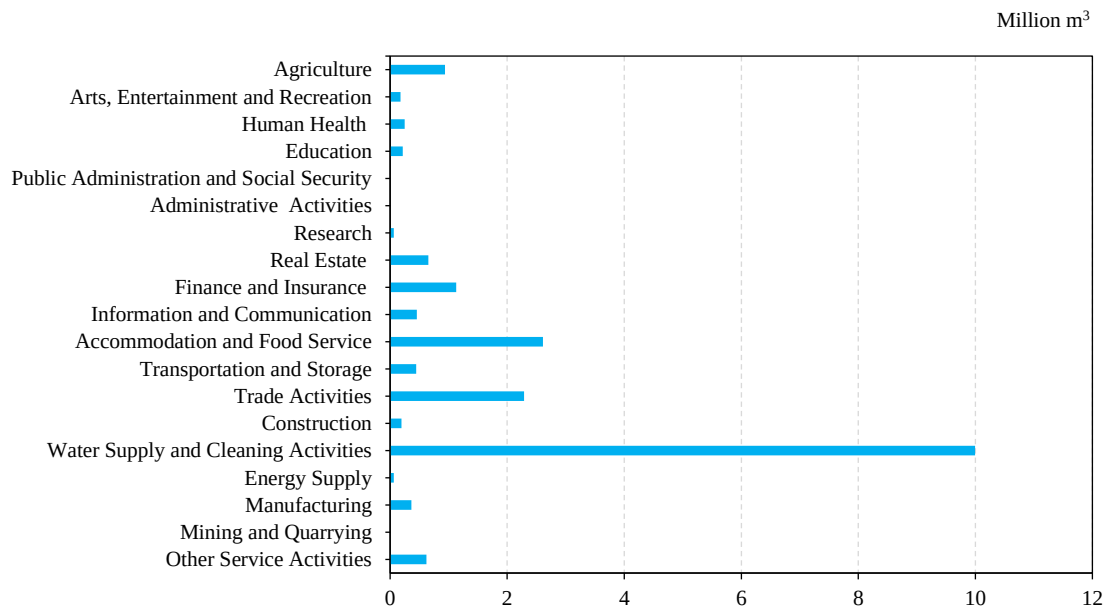


Figure 8. Water consumption by economic sectors in Phuket in 2015

Based on the statistical data, the total water consumption in Phuket in 2015 was approximately 20.5 million m³. From the input-output analysis, the largest portion of water consumption was attributed to Water supply and cleaning activities. Ranked in first place, this sector consumed roughly 10 million m³ as shown in Figure 8. It is associated with residential living serving essential functions such as water supply

for daily cooking and facilitating cleaning and sanitation activities. Other sectors closely related to tourism also contributed significantly to water consumption. At the second place, Accommodation and Food Services consumed about 2.6 million m³. Trade activities had the third largest consumption with approximately 2.3 million m³. This result is also in the line with a study discussing the situation in Hawai'i-

one of the most famous tourist islands. The study in Hawai'i indicates that residents are also the most substantial consumers, accounting for 55% of the island's water consumption, while hotel and resorts accounted for only 5% of the total water consumption (DeMaagd et al., 2022). Another study also reveals that residents commanded the greatest portion of water consumption on the Island of Ibiza in Spain's, accounting for 84.4% of the island's total water usage (Pérez et al., 2020).

Given that the Provincial Waterworks Authority is one of the main water sources for hotels, along with private suppliers, and water collected and produced by the hotels (Sattraburut et al., 2024), its supply is pretty sensitive to fluctuation in tourist numbers, as indicated in Figure 9. It surged during the tourist season, which is typically during the dry season from December to March (Sattraburut et al., 2024). The water sold from this source peaked in April, primarily due to the occurrence of Songkran, one of Thailand's largest festivals which attracts many tourists and also involves a lot of water. The tourist number during the high season is 42% higher than during the low season, leading to the notable increase in water demand from tourism. Moreover, the reduced precipitation during dry season also exacerbates water shortage on this island during tourism periods. A project worth 3.5 billion THB to construct a pipeline from Phang Nga to enhance water availability in Phuket, was approved in 2019 (The Phuket News, 2020). If this project is completed by 2040 to provide sufficient amount of

water (33.18 million m³) for the tourism sector (Sattraburut et al., 2024), merely Accommodation and Food Service could generate revenue of 280.25 billion THB for Phuket, which is 80 times the construction cost of the pipeline.

Not only the water quantity, but the estimated result also reveals that 305.5 t N equivalent was emitted in 2015 in, equivalent to the nitrogen content in approximately 664 tons of urea fertilizer applied in a year. These emissions contribute to local eutrophication, a process where excess nutrients lead to overgrowth of algae in water bodies, affecting water quality. As seen in Figure 10, Water Supply and Cleaning Activities emerged as the primary contributor to eutrophication with 169.5 t N equivalent. Following in second place was Energy Supply, contributing 93.7 t N equivalent. Transportation and Storage contributed the third largest share with 27.9 t N equivalent. In terms of emission-related activities, nearly 50% of the nitrogen emissions originated from wastewater treatment. Furthermore, approximately 0.06 million m³ per day of untreated wastewater was discharged directly into the environment in 2015. This escalating degradation underscores the urgent need for a response to improve the Phuket's wastewater treatment capacity and management since it affects not only the daily lives of its residents but also tourism reputation such as Bang Tao beach's case, where untreated wastewater entering a local canal caused the water to turn black, impacting the beach's environment and tourism activities. (The Phuket News, 2019).

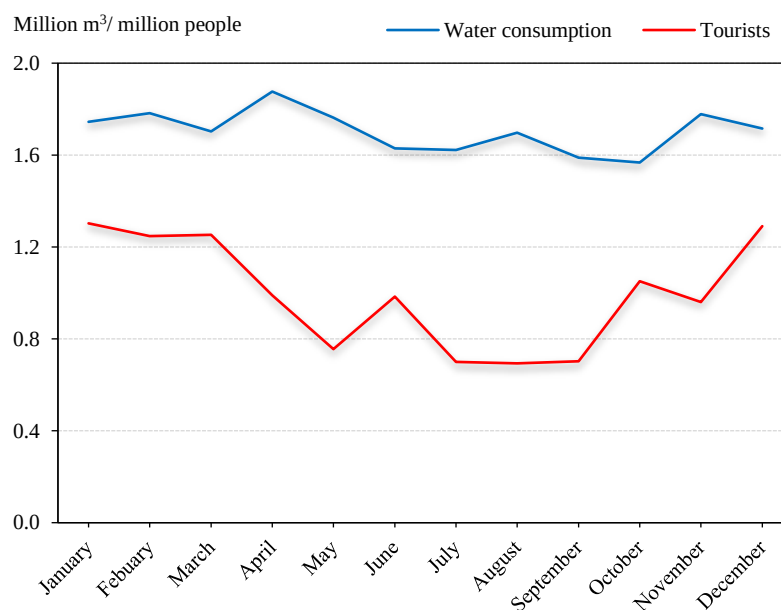


Figure 9. Monthly water sales (million m³) by the Provincial Waterworks Authority and tourist numbers (million people) in Phuket in 2015

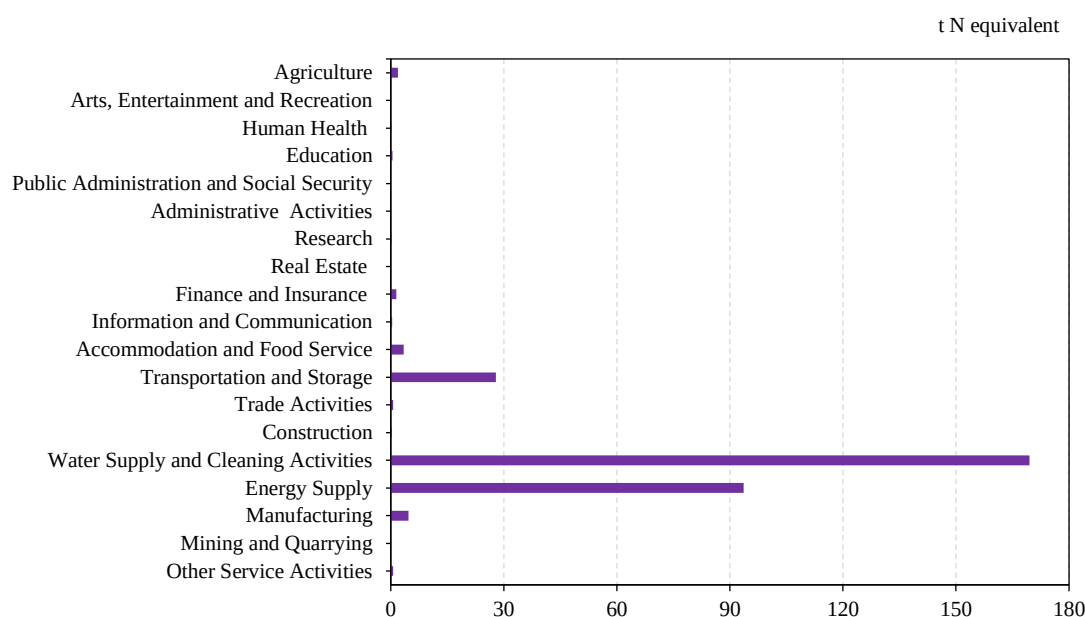


Figure 10. Eutrophication by sector in Phuket in 2015

As presented above, the main contributors for all considered categories were industries related to tourism including Accommodation and Food Service activities, Transportation and Storage, Wholesale and retail trade and repair of motor vehicle. Industries associated with the local residents' consumption such as (i) Energy Supply, as well as (ii) Water supply and cleaning activities also made noteworthy contributions. Other sectors with less direct relevance to tourism, such as Manufacturing and Education, resulted in less negative environment impacts. Since there was not an enormous demand of infrastructure construction for tourism at that time, the adverse effect on this island's environment from the construction sector was also not substantial.

3.2 Environmental costs and green gross provincial product of Phuket

Phuket's total environmental costs in 2015 were 6.7 billion THB with depletion and degradation contributing 60% and 35%, equaling 4 and 2.4 billion THB, respectively. The remaining of 5%, equaling to 310 million THB, was contributed by defensive cost, which is six times less than degradation cost.

The primary component of degradation cost was global warming with a contribution of 2.2 billion THB, followed by land use with 147 million THB. On the other hand, a loss of 1.6 billion THB was attributed to problems related to human health, more than twofold of the loss caused by damage to ecosystems.

Fossil resource scarcity and global warming emerged as the two main drivers with the most substantial impacts on Phuket's environmental costs, as illustrated in Figure 11. These figures could be used in assessing the environmental damage caused by various issues and raising public awareness to address and improve environmental problems.

Phuket's defensive costs were primarily spent on the construction and expansion of infrastructure for waste disposal and wastewater treatment. The expense on infrastructure construction for wastewater treatment accounted for 90% of the total defensive cost. The details of defensive costs are listed in Table A5 in the supplementary file.

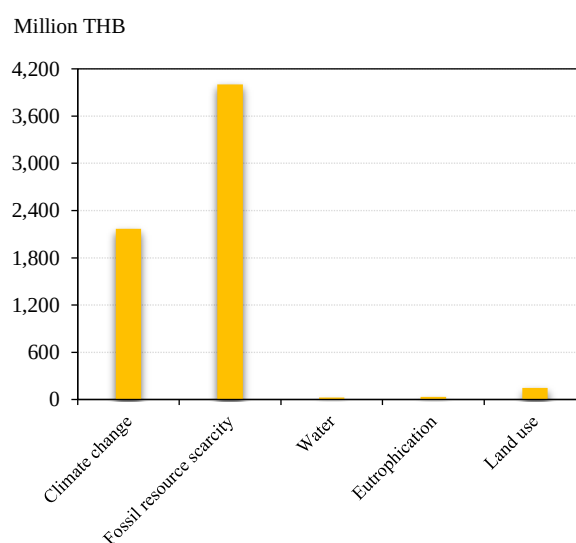


Figure 11. Distribution of environmental costs (except defensive costs) across major impact categories in Phuket in 2015

From an economic sector perspective, the sector incurring the highest environmental cost was Energy Supply, totaling 2.6 billion THB. Accommodation and Food Service secured the second position with 707.1 million THB. The third place was Transportation and Storage with 586.9 million THB. Trade Activities followed closely in fourth place with 402 million THB.

Industries related to tourism including Transportation and Storage, as well as Accommodation and Food Service were significant contributors to the provincial environmental costs. This is consistent with other studies suggesting that transportation (Stefanica, 2017) and accommodation (Mota et al., 2024) significantly contributed to the environmental burden of tourism. When the patterns of major impacts on tourism in different locations are quite similar as presented (Campos et al., 2024), effective policies or innovative solutions in one area can be a good model for other areas around the world.

The consumption of residents and government greatly contributed to the environmental costs of two sectors (i) Energy Supply, as well as (ii) Water Supply and Cleaning Activities. This consumption accounted for 73.5% and 60.3% of the total environmental costs incurred by these two sectors, respectively. This highlights the essential role that residents and government play in improving Phuket's environmental performance. Therefore, it is crucial to establish policies that promote and raise awareness among residents regarding responsible consumption through various approaches, such as green procurement (Wang et al., 2021), which can help fulfill their needs while preserving the environment (Liu and Tobias, 2024).

Since Phuket is a tourism-based island, the primary pillars of its economy are industries associated with tourism. They contributed significantly to the Phuket GPP. Accommodation and Food Services - one of the vital components of tourism, plays a major role by contributing 69.1 billion THB to the GPP. Transportation and Storage came in second place with 34.6 billion THB. Trade Activities was the third largest contributor with 8.9 billion THB.

Despite causing potential economic loss at approximately 6.6 billion THB, this amount is not deemed significant compared to the GPP of Phuket. The GGPP of Phuket in 2015 was 160 billion THB, equal to 96% of the GPP of Phuket. As shown in Figure 12, which presents both GPP and GGPP by sector, the sectors encompassing the demand of local residents such as (i) Energy Supply, as well as Water

Supply and Cleaning Activities exhibited the lowest sectoral GGPP. On the other hand, tourism-driven sectors generate substantial economic value while accounting for a comparatively smaller share of environmental costs relative to their contribution to GPP. This distinction indicates that sustainability efforts in Phuket should adopt a dual approach: promoting responsible consumption and resource efficiency among residents, while guiding tourism activities toward low-impact growth through improved infrastructure, cleaner technologies, and effective planning. Together, coordinated actions targeting both residents and tourists are essential for maintaining economic benefits while reducing environmental pressures on the island. It should be noted that the comparison between residents and tourists in this study is based on aggregate sectoral demand rather than normalization on a per-capita basis. This approach reflects the overall pressure exerted by different demand groups on provincial economic sectors and highlights the importance of responsible consumption by residents in achieving sustainable development on the island.

As can be seen, in Phuket, tourism-related sectors such as Accommodation and Food Services, and Transportation and Storage are major contributors to provincial GDP, while sectors such as Energy Supply and Water Supply and Cleaning Activities account for the highest environmental costs. This divergence highlights that sectors driving economic growth are not always those imposing the greatest environmental burden. From a policy perspective, this finding underscores the need for differentiated strategies: tourism planning should focus on improving resource efficiency and environmental performance in high-GDP tourism sectors, whereas environmental policies should prioritize demand-side management and cleaner production in sectors with high environmental costs. For resource management, aligning economic development objectives with environmental performance through instruments such as green procurement, efficiency standards, and integrated planning is essential for enhancing the sustainability of tourism-based islands.

However, the environmental costs presented are only from the five impact categories considered. There are many other impacts that are problematic to quantify, such as coral bleaching, floods and landslides, which cause deaths. In addition, the data for defensive costs extracted from government reports are only calculated for items that are clearly identified

for environmental protection efforts. However, in practice, there are environmental costs included in other budget categories, such as travel expenses paid for environmental care activities. If we add together

environmental costs that are both clearly quantifiable and difficult to accurately assess, the cost should be a lot higher and there would be some losses that cannot be recovered.

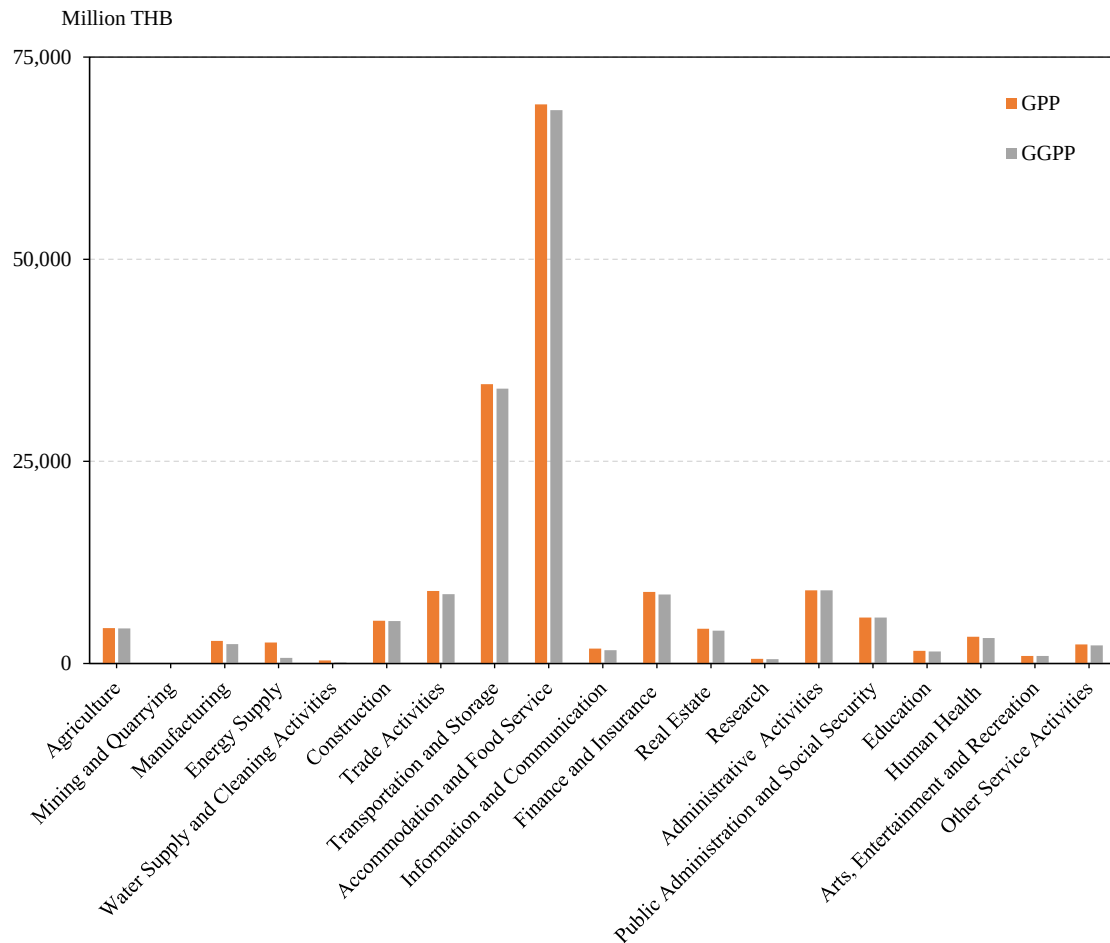


Figure 12. Phuket gross provincial product (GPP) and green gross provincial product (GGPP) across major economic sectors in Phuket in 2015

Acknowledging that environment plays a crucial role in tourism development, the primary sectors contributing to the island's GPP, and considering the substantial GGPP of this island after accounting for environmental costs, it is recommended to increase the budget allocated to environmental protection to mitigate the existing burden, prioritizing urgent issues significantly affecting to residents' daily lives and tourism. Such support also can also facilitate sustainable development.

The use of national cost factors for provincial-level valuation may influence the absolute magnitude of environmental cost estimates, as local socioeconomic conditions may differ from national averages. However, such effects are expected to have a limited impact on the relative comparison across

sectors and on the overall interpretation of GGPP results.

A sensitivity analysis was conducted to assess the influence of uncertainty in monetization factors on environmental cost estimates. The monetization factors were varied by $\pm 10\%$, and the results show a proportional response across all impact categories, including climate change, fossil fuel scarcity, water scarcity, and eutrophication. Specifically, a 10% increase in monetization factors led to a corresponding 10% increase in environmental costs for each category, indicating a linear relationship. At the aggregate level, the total environmental cost of Phuket in 2015 increased from 6,378.56 million THB in the base case to 7,001.67 million THB under the +10% scenario. These results suggest that while the absolute

magnitude of environmental costs is sensitive to monetization assumptions, the relative contributions of impact categories and the overall interpretation of the results remain robust.

4. CONCLUSION

This study outlines the procedure for constructing a provincial input-output table and subsequently, the method to apply it for the environmental assessment of Phuket, an island having tourism-based economy. It also contributes to the literature in the field of economic accounting integrating environmental assessment.

It is worth noting that for a tourist island like Phuket, which relies on external goods, it is recommended to use input-output tables for environmental burden allocation. This is particularly valuable for industries that do not have production lines on this island, such as gasoline refinery, as the data provided is the costs associated with goods distribution. Unlike national-scale input-output tables, which capture cradle-to-gate impacts of industries, island-level tables mainly provide information on the distribution of goods. Nevertheless, these data can still be used to evaluate the environmental impacts of economic activities on the island.

The calculated outcomes reveal that Phuket's overall environmental costs reached nearly 6.6 billion THB. The predominant components of the environmental cost were degradation cost and depletion cost, primarily driven by fossil resource scarcity and global warming with 90% contribution.

Sectors linked to tourism, such as transportation and repair, alongside Accommodation and Food Services activities, emerged as substantial contributors to the environmental costs of the province. The findings also indicate that residents and government are the primary drivers of the sectors that have a significant impact on environmental costs, including (i) Energy Supply which stands for electricity, gas, steam, and air conditioning supply, as well as (ii) Water Supply and Cleaning Activities which stands for water supply, sewerage, waste management and remediation activities. This underscores the crucial roles that residents and government play in enhancing Phuket's environmental performance.

Given the different economic structures of provinces compared to countries, conducting assessment at provincial level is crucial to identify the appropriate areas of focus to establish effective policy and management targets. Sectors linked to tourism, for

examples, Accommodation and Food Service, as well as Transportation and Storage, received higher earnings but also incurred more significant environmental burdens compared to other industries. It also suggests that, in addition to policies aimed at fostering economic development, there should be policies targeting the environmental performance of sectors related to tourism.

Given the importance of environment to tourism, the findings suggest boosting environmental spending aiming at enhancing environmental quality, resolving current environmental issues, and advancing sustainability efforts.

Some degree of uncertainty arises from the use of the CIQ method to regionalize the national input-output table, particularly in provinces with a service- and tourism-oriented economic structure such as Phuket. While the CIQ approach may not fully capture all import leakages associated with tourism-related activities, it remains a practical approximation given current data availability. Potential deviations between national and provincial production structures may affect the magnitude of estimated inter-industry linkages; however, the overall economic relationships and relative sectoral contributions are still reasonably represented. Consequently, the resulting GGPP estimates should be interpreted as indicative measures of green economic performance rather than precise point estimates.

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AUTHOR CONTRIBUTIONS

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Anh Thi Nguyen, Shabbir H. Gheewala, Kritana Prueksakorn; Writing - review and editing, Hong Anh Thi Nguyen, Shabbir H. Gheewala, Kritana Prueksakorn; Funding acquisition, Hong Anh Thi Nguyen, Shabbir H. Gheewala, Kritana Prueksakorn; Resources, Shabbir H. Gheewala, Kritana Prueksakorn; Supervision, Shabbir H. Gheewala, Kritana Prueksakorn.

DECLARATION OF CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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Suitability of Characteristic Wastewater Treatment Technologies: An Approach to Water Environment Protection in Major River Basins in the Former Binh Thuan Province, Vietnam

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ABSTRACT

In 2025, Binh Thuan Province was merged into Lam Dong Province as part of a broader restructuring initiative by the Vietnamese government. In the former Binh Thuan Province, Vietnam, increasing pollution pressure in river basins (where wastewater is received) requires identifying and applying wastewater treatment technologies suitable to the actual situation of the wastewater sources. This study conducted a multi-criteria analysis (MCA) combined with the weighted sum method and visualized through radar charts to assess the suitability of treatment technologies, identify operational incidents, evaluate impact levels and prioritize rehabilitation of wastewater treatment systems (WWTSs) currently applied to five typical wastewater types: domestic, industrial, seafood processing, livestock and hospital wastewater. A set of criteria comprising 22 sub-criteria in four groups (technical, environmental, economic, social) is applied and the criteria are quantified based on field surveys and expert consultations. Results showed that domestic WWTS achieved the highest score (75/100) reflecting stable performance and a high level of suitability, while seafood processing WWTS scored lowest (50.625/100) due to high costs and unstable efficiency. Industrial WWTS (68.125/100), livestock WWTS (64.375/100) and hospital WWTS (68.75/100) systems performed moderately, with good technical outcomes but constraints in cost, energy use and emissions. Recurrent incidents such as aeration failures, sludge flotation and odor generation were common, though generally remediable. Seafood processing and industrial WWTS were prioritized for urgent rehabilitation. This study provides essential data and a practical MCA-based decision-support framework to improve existing WWTSs under local environmental and operational conditions, thereby supporting water resource protection in Vietnam's river basins.

HIGHLIGHTS

- First MCA framework applied to wastewater treatment technologies in Binh Thuan Province.
- Novel set of 22 sub-criteria integrating four sustainability dimensions.
- Five typical wastewater types were evaluated for current treatment technology suitability.
- Proposed technical fixes prioritized high-risk but feasible interventions.

1. INTRODUCTION

The former Binh Thuan Province (now part of Lam Dong Province) is located in the southern part of the South-Central Coast of Vietnam. It consists of 88 river basins, seven of which are classified as major

basins: the Long Song, Luy, Cai Phan Thiet, Ca Ty, Phan, Dinh and La Nga rivers. These rivers collectively drain a basin area of more than 5,000 km² and flow through industrial and residential areas of the province (Huynh et al., 2024; Binh Thuan Statistics

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Office, 2024). They are also the places that receive the wastewater stream generated across the region. The results of the load-carrying capacity calculations of major river basins in the former Binh Thuan Province during the 2022-2023 period indicate that surface water has been primarily polluted by organic matter (COD, BOD₅) and nutrients (NH₄⁺, NO₃⁻, PO₄³⁻). Most river basins have exceeded their carrying capacity for the analyzed parameters (Huyhn et al., 2023; Huyhn et al., 2025).

A distinctive characteristic of the former Binh Thuan Province is that a large number of wastewater sources discharge less than 10 m³/day and are widely distributed. They primarily consist of five types of sources: domestic, centralized industrial zones, livestock, seafood processing and hospital wastewater. Many studies indicate that these wastewater sources are typically characterized by high loads of organic matter, nutrients and pathogens, with BOD, COD, TSS, and TN levels often exceeding standards (Burton and Turner, 2003; Verlicchi et al., 2010; Muthukumar and Baskaran, 2013; Tchobanoglous et al., 2014). If untreated or inadequately treated, such wastewater contributes to ecological degradation, oxygen depletion, odor generation and the spread of pathogens, thereby posing serious environmental and public health risks (Ortigara and Connor, 2017; Jordan and Eaton, 2024).

Although investment in wastewater treatment has increased in the former Binh Thuan Province, field investigations reveal that many treatment facilities still do not comply with national standards, highlighting the need to reassess the suitability of existing treatment technologies. Environmental researchers argue that a technology aligned with the principles of sustainable development should be characterized by the lowest possible costs (both capital and operational), technical and legal feasibility, proven effectiveness in pollution control and acceptance by the local community (Ferguson et al., 2003). Thus, an appropriate technology does not necessarily have to be the most advanced or expensive option, it should be capable of reaching discharge standards while being well-adapted to the local natural, economic and social conditions. In practice, such multidimensional factors are often insufficiently considered in Vietnam, resulting in suboptimal technology selection and inefficient resource use. Meanwhile, many studies have shown that sustainable development is built on

four essential aspects: technical, economic, environmental and social (Omran et al., 2021).

Multi-Criteria Analysis (MCA), also referred to as Multi-Criteria Decision Analysis (MCDA) is a systematic methodology that combines the hierarchical structures of a problem with priorities for alternatives in many fields (Akdogan and Guven, 2023). In the environmental field, the integration of these criteria through MCDA methods has become a widely adopted tool in wastewater management and the selection of appropriate treatment options (Plakas et al., 2016; Lizot et al., 2021; Ko et al., 2024). In recent studies, notably in China, Multi-Dimensional Comprehensive Assessment (MDCA) represents a specific extension of MCDA that explicitly integrates environmental, economic, social and technical dimensions for sustainability-oriented evaluations. To guide the selection of wastewater treatment technologies in a scientific and rational manner, it is necessary to apply technology assessment methods based on MCDA approaches, including the MDCA framework. Establishing an MDCA framework with a sustainability-based approach is essential to identify potential technologies, as it begins with defining and scoring indicators, assigning weights, selecting appropriate evaluation models, conducting uncertainty analysis and ultimately determining preferred alternatives (Li et al., 2023).

In view of the above situation, this study conducted a multi-criteria analysis (MCA) to evaluate the suitability of existing wastewater treatment technologies for typical wastewater types in the former Binh Thuan Province. In Vietnam, a case study applying MCA methods has also been conducted, in which life cycle assessment (LCA) was integrated to select sustainable wastewater treatment scenarios for Toan Thang Town in Vietnam (Pham et al., 2010). However, that study was limited to the proposal of hypothetical scenarios. In fact, MCA-based studies in Vietnam remain very limited, with only a few applications and a lack of validation using real treatment systems. The present study focuses on real wastewater treatment systems in the former Binh Thuan Province, aiming to identify optimal solutions adapted to wastewater characteristics and local conditions. The goal was to improve existing treatment facilities, enhance effluent quality, minimize secondary pollution risks to receiving waters and support sustainable water resource management in this area.

2. METHODOLOGY

2.1 Study area

The study was conducted across seven major river basins stretching from the north to the south of the former Binh Thuan Province (Figure 1), covering a total catchment area of about 6,890 km², which represents nearly the entire provincial territory.

The former Binh Thuan Province, located in the south-central coastal region of Vietnam, covers a total area of 7,943.93 km², with geographical coordinates

from 10°33'42" to 11°33'18" N latitude and from 107°23'41" to 108°52'42" E longitude (Binh Thuan Statistics Office, 2024). The study area has a tropical monsoon climate with two distinct seasons: a rainy season from May to November and a dry season from December to April. Annual rainfall varies considerably, ranging from 2,000-2,564 mm in the northwest and 1,400-1,600 mm in the south to only 730-1,110 mm in the northeastern and central regions (Binh Thuan DoNRE, 2020).



Figure 1. Study area location

2.2 Survey and data collection methods

2.2.1 Characterization survey of typical wastewater types

The wastewater sources were surveyed by river basin at the former Binh Thuan Province for the first time, including information on generation sources, the number of wastewater-generating facilities, discharge locations, total discharge volume and wastewater composition characteristics. The data were collected and classified into five major types of wastewater: domestic, centralized industrial zone, seafood processing, livestock and hospital wastewater.

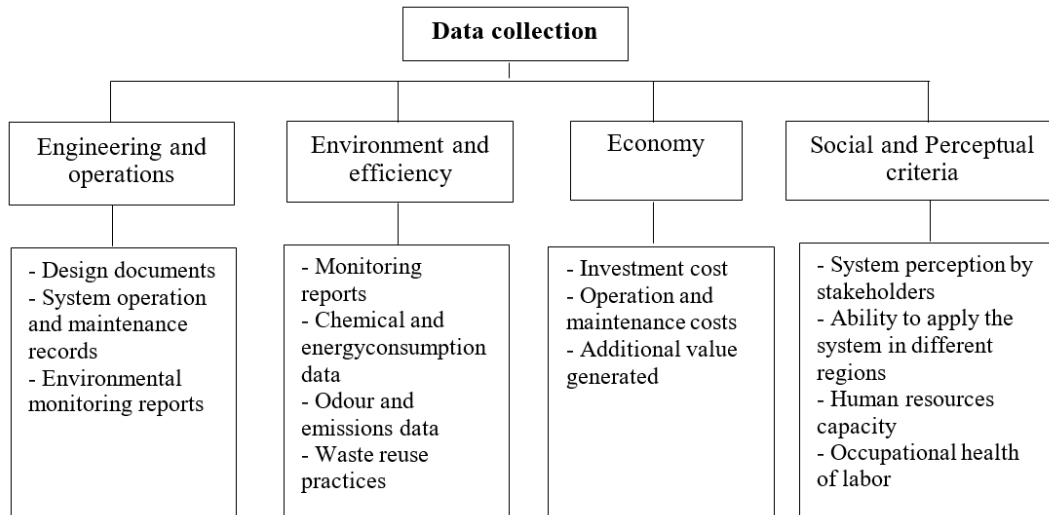
2.2.2 Survey of wastewater treatment processes

The survey was conducted at wastewater-generating facilities in the former Binh Thuan Province. The study focused on assessing treatment

technologies and system performance in removing typical pollution parameters (pH, Temperature, TSS, Turbidity, Color, BOD₅, COD, NH₄-N, Total N, Total P, PO₄-P, Oil and grease compounds, Total surfactants, Residual chlorine, Coliforms) in accordance with MoNRE (2008), MoNRE (2010), MoNRE (2011), MoNRE (2015), and MoNRE (2016) as well as evaluating operating conditions, treatment status and environmental monitoring practices.

2.2.3 Investigation and data collection of WWTSs

In order to establish a basis for developing a set of criteria for assessing technology suitability, the study combined multiple data sources derived from the results of actual investigations and surveys. The collected data includes:



2.3 MCA method for assessing the suitability of wastewater treatment technologies

2.3.1 Structured interviewing method

The interviewees included environmental experts. The sample size was calculated for expert interviews will be calculated using the following formula (Yamane, 1967):

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

Where; n is the sample size, N is the population size, and e is allowance for inaccuracy (5%).

2.3.2 Identification and quantification method for criteria groups

The assessment of the suitability of wastewater treatment technologies was carried out using an MCA framework, including four main criteria groups: technical (A), environmental (B), economic (C) and social (D) with a total of 22 sub-criteria (Table 1) as suggested by VEA (2011) and Li et al. (2023) (except for cost-related sub-criteria, which were determined based on actual costs at the time of the study).

2.3.2.1 Assign weights to criteria groups

The weights of the criteria groups were determined based on expert opinions combined with actual conditions at wastewater treatment plants. The technical and environmental criteria groups were considered the most important, with each assigned a weight of 0.3. The economic and social criteria groups were assessed as having a lower level of importance, with each assigned a weight of 0.2. The total weight of the four criteria groups equals 1.

2.3.2.2 Scoring method

The overall evaluation score was normalized to a 100-point scale, in which the score for each main criteria group (A, B, C, D) was calculated as the sum of the scores of its corresponding sub-criteria (formula 2) (VEA, 2011).

$$A = \frac{n}{i=1} A_i \quad B = \frac{n}{j=1} B_j \quad C = \frac{n}{p=1} C_p \quad D = \frac{n}{q=1} D_q \quad (2)$$

When; $A + B + C + D = 100$

Where; A_i , B_j , C_p , and D_q are the scores of the sub-criteria within each corresponding criteria group, and n is the number of sub-criteria belonging to each criteria group. Each sub-criterion score was calculated using Formula 3.

$$B_j = c_j \times w_j \quad (3)$$

Where; c_j is the score of the sub-sub-criterion within the j-th sub-criterion, and w_j is the weight of the main criterion group containing the sub-criterion.

The scoring of a sub-sub-criterion (c_j) depends on the ranking of its relative importance. Within the same sub-criterion, if all sub-sub-criteria are of equal importance, the evaluation score assigned to each is identical and equal to $\bar{X}$ (the average score of the sub-subcriteria). Conversely, if the sub-sub-criteria are ranked, the scores are assigned in descending order of importance, as follows:

$$c_j = (m - r) \times \bar{X} \quad (4)$$

Where; m is the total number of sub-sub criteria, r is rank of the sub-sub-criterion ($r=1$ indicates the highest importance) and $\bar{X}$ is the average score of the sub-sub-criteria.

Table 1. Set of construction criteria to assess the suitability of wastewater treatment technology

Group	Code	Criteria	Sub-Criteria
Technical	TC1	Treatment efficiency of the technology	pH, BOD, COD, TSS, Coliform
	TC2	Treatment efficiency of the technology under abnormal operating conditions	Pump failure, oxygen deficiency, valve misoperation, nutrient/microbial imbalance Note: The impact of various incidents on the treatment efficiency of the technology is regarded as equivalent.
	TC3	Frequency of system maintenance and servicing	2 times/month, 1 time/month, 1 time/2 months, 1 time/3 months
	TC4	Service life and structural/equipment durability	Repairs: >5 years, >3 years, >1 year
	TC5	Availability and ease of replacement for spare parts and equipment	Equipment and components available locally; Equipment and components not available locally (but available in Vietnam); Equipment and components must be imported.
	TC6	Compatibility of wastewater treatment technology with workers' technical proficiency	Highly suitable, Suitable, Not suitable
	TC7	Impact of system incidents or malfunctions on treatment performance	Uncontrolled exceedance to No impact
Environmental	TC8	Potential for the reuse of secondary outputs (e.g., biogas, organic sludge)	None, Partial, Full
	TC9	Chemical consumption in wastewater treatment (kg/m ³ /day)	From <0.3 to >0.5 m ³ /day
	TC10	Energy consumption (kWh/m ³ of wastewater)	From <0.5 to >1.5 kWh/m ³
	TC11	Noise impact on system operators and surrounding communities	Significant without control to no impact
	TC12	Probability of environmental incidents (e.g., chemical spills, wastewater or sludge discharge into the environment)	From >4 times/year to no cases/year
	TC13	Pollutant emissions into soil, water and air	No pollutant emissions, Gases, Secondary emissions
Economic	TC14	Capital cost for construction and equipment installation (VND/m ³ of wastewater)	From <10 million to >15 million VND/m ³
	TC15	Operating cost of the system (VND/m ³ of wastewater)	From <2,000 to >8,000 VND/m ³
	TC16	Treatment cost of wastewater (VND/m ³)	From <4,000 to >15,000 VND/m ³
	TC17	System maintenance cost (including microbiological, equipment, electrical and aeration components)	From <8 million to >15 million VND/year
	TC18	Revenue potential from secondary outputs of the wastewater treatment system	Yes, No
Social	TC19	Aesthetic and visual aspects of the system	From not suitable to very suitable
	TC20	Adaptability to regional conditions (e.g., climate, weather)	From site-specific to universal
	TC21	Primary sources of human resources for system management and operation	Experienced workers, engineers and environmental engineers
	TC22	Health impacts on system operators	From significant to none

Note: "TC"- sub-criteria, "VND"- Vietnamese Dong (currency of Vietnam) (IPCC, 2006; MoNRE, 2008; MoNRE, 2010; MoNRE, 2011; VEA, 2011; GoV, 2014; MoNRE, 2015; MoNRE, 2016; GoV, 2020)

2.3.3 Weighted sum method combined with radar chart

The simple additive weighting method (SAW) is one of the most popular multi-criteria decision-making techniques due to its simplicity and efficiency in processing quantitative data (Ayyıldız and Özçelik, 2018). In this study, the SAW method was applied to evaluate and determine the level of impact of technical incidents in wastewater treatment systems. The method is based on the principle of weighted

aggregation of independent criteria and allows the quantification of the severity of each incident.

Survey data were collected for five types of wastewater in the former Binh Thuan Province. Assessments were standardized in quantitative form through five level (1-5) or three level (1-3) rating scales depending on the specific criterion, including the level of impact of the incident (5=very severe to 1=very minor), the priority of improvement (5=unnecessary to 1=mandatory rehabilitation) and consensus regarding the solution (3=disagree to

1=agree). The average score at each rating level was calculated according to Formula 5. The final results were visually presented using a spider diagram to clarify the level of impact and priority of improvement of incidents.

$$A = \frac{\sum a_i}{N} \quad (5)$$

Where; A is the average score of each factor, a_i is rating score ($a_i = i \times n$), i is rating value of level i (ranging from 1 to 5 or 1 to 3), n is the rating frequency for each level, and N is total number of evaluation responses.

3. RESULTS AND DISCUSSION

3.1 Characteristics of typical wastewater types

3.1.1 Characteristic composition of wastewater sources

The ranges of wastewater quality parameters recorded during the study period are presented in Table 2, where considerable variability is observed across different wastewater sources.

Table 2 presents the characteristic composition of five typical wastewater types in the former Binh Thuan Province. Domestic wastewater generally matched reported ranges (Tchobanoglous et al., 2014), though with slightly lower $\text{NH}_4\text{-N}$ concentrations. Industrial effluents exhibited very high organic loads

(BODs up to 1,156 mg/L; COD up to 3,200 mg/L) and contained oil, grease and surfactants, reflecting their complex composition (Lam et al., 2014). Seafood processing wastewater showed moderate pollution levels compared to previous studies (Muthukumaran and Baskaran, 2013; Vidya et al., 2020), but elevated residual chlorine concentrations (approximately 130 mg/L) posed risks of aquatic toxicity. Livestock wastewater contained extremely high organic concentrations (BODs up to 8,900 mg/L; COD up to 12,000 mg/L), nearly twice the typical ranges reported elsewhere (Burton and Turner, 2003; Chastain and Vanotti, 2003). Hospital wastewater presented hazardous loads of organics, nutrients and pathogens, comparable to the findings of Verlicchi et al. (2010), with coliform counts up to 10^7 MPN/100 mL.

Overall, these findings highlight heterogeneous and often severe pollution levels, emphasizing the need for appropriate treatment technologies and management measures.

3.1.2 Characteristics of wastewater treatment systems

Each of the five representative wastewater types in the former Binh Thuan Province is subject to specific treatment processes, as shown in Figure 5. Although the processes differ in technology, they all employ a combined treatment approach consisting of mechanical, biological and physicochemical methods.

Table 2. Characteristics of wastewater types in the former Binh Thuan Province

No.	Parameter	Unit	Domestic wastewater Range	Industrial zone wastewater	Seafood processing wastewater	Livestock wastewater	Hospital wastewater
1	pH	-	7.52-8.01	6.5-8.0	5.99-6.51	6.1-7.9	4-10
2	Temperature	(°C)	-	28.5-32.0	-	-	-
3	TSS	mg/L	156-205	484-512	440-490	680-1,200	75-250
4	Turbidity	NTU	-	-	-	420-550	-
5	Color	Pt-Co	-	-	-	350-870	-
6	BOD ₅	mg/L	156-173	925-1,156	768-816	3,500-8,900	120-200
7	COD	mg/L	328-368	2,420-3,200	1,319-1,581	5,000-12,000	150-250
8	$\text{NH}_4\text{-N}$	mg/L	13.6-14.5	55.6-78.2	67.2	-	80-120
9	Total N	mg/L	-	168-172	105-151.9	220-460	50-90
10	Total P	mg/L	-	-	-	36-72	-
11	$\text{PO}_4\text{-P}$	mg/L	3.53-4.21	-	-	-	-
12	Oil and grease compounds	mg/L	6.45-8.36	-	123.1-143.8	-	-
13	Total surfactants	mg/L	3.57-4.69	-	-	5-58	-
14	Residual chlorine	mg/L	-	-	129.7-132.6	-	-
15	Coliforms	MPN/100 mL	$21\text{-}95 \times 10^5$	9×10^3	$15 \times 10^4 - 46 \times 10^5$	14×10^3	$10^5\text{-}10^7$

Note: “-” Undetermined

The survey revealed that wastewaters is conveyed to a receiving sump or equalization tank to stabilize flow and quality prior to subsequent treatment in the preliminary stage. Biological processes, including aerobic (aerotank), anoxic and anaerobic (UASB-Upflow Anaerobic Sludge Blanket, biogas) systems, are strategically integrated to facilitate the removal of organic matter and nutrients (N, P). For high-strength wastewater streams, such as those from livestock operations and seafood processing, coagulation-flocculation, flotation and physicochemical sedimentation are incorporated. In addition, the treatment processes include disinfection and sludge management.

The quality of treated effluent in all treatment systems is required to comply with the permissible limits specified in the relevant national technical regulations, including QCVN 14:2008/BTNMT (domestic wastewater), QCVN 40:2011/BTNMT (industrial wastewater), QCVN 11-MT:2015/BTNMT (seafood processing wastewater), QCVN 62:2016/BTNMT (livestock wastewater) and QCVN 28:2010/BTNMT (hospital wastewater).

3.2 Determination of the maximum score for the set of technology suitability assessment criteria

The study quantified the maximum scores of the four main criteria groups (Figure 2), the sub-criteria and sub-sub criteria. TC1 (Treatment efficiency of the technology) and TC2 (Treatment efficiency of the technology under abnormal conditions) have equivalent sub-subcriteria. Therefore, the score for each sub-subcriteria is equal and corresponds to $\bar{X}$ as described in section 2.3.2.2. The remaining criteria, which include ranking levels, were assigned scores according to their respective ranking levels. The results of the maximum scores of the sub-criteria are presented in Table 3.

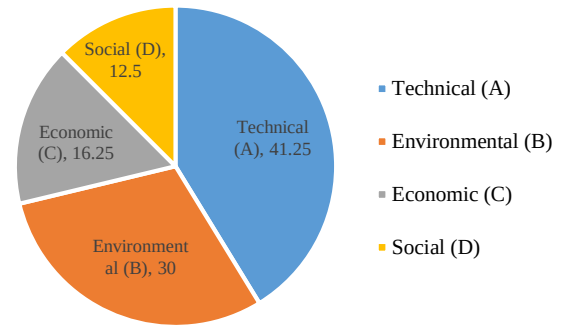


Figure 2. Maximum scores for the main criteria groups

The score distribution is designed to identify key determinants in evaluating the suitability of wastewater treatment technologies.

In this study, the maximum scores of the 22 sub-criteria (Table 3) indicate that treatment efficiency (TC1, TC2) was given the highest weights, reflecting its primary importance in technology selection. Criteria related to operation and environmental safety (TC3-TC13) were assigned medium scores, highlighting their supportive role in overall performance. In contrast, cost-related aspects (TC14-TC17) received relatively lower weights, suggesting that while economic considerations are relevant, they are not prioritized over technical effectiveness. Overall, the scoring distribution emphasizes treatment performance and environmental protection as the key determinants in evaluating the suitability of wastewater treatment technologies.

While the present study employed a distinct multi-criteria analysis (MCA) framework compared with previous works, the outcomes are consistent with earlier studies (Srivastava and Singh, 2022; Eseoglu et al., 2022; Selerio, 2024), confirming that treatment performance and environmental protection outweigh cost and operational factors in the selection of wastewater treatment technologies.

Table 3. Maximum scores of the sub-criteria

Criteria groups							
Technical		Environmental		Economic		Social	
Code	Maximum Score	Code	Maximum Score	Code	Maximum Score	Code	Maximum Score
TC1	9.375	TC8	3.75	TC14	3.75	TC19	3.75
TC2	7.50	TC9	5.625	TC15	3.75	TC20	2.50
TC3	5.625	TC10	5.625	TC16	3.75	TC21	3.75
TC4	3.75	TC11	5.625	TC17	3.75	TC22	2.50
TC5	3.75	TC12	5.625	TC18	1.25		
TC6	5.625	TC13	3.75				
TC7	5.625						

3.3 Assessment of the suitability of wastewater treatment technologies

Figure 3 indicates significant differences in the suitability levels of wastewater treatment technologies. Among the five systems surveyed, the domestic wastewater treatment system (WWTS) achieved the highest overall score (75/100), performing particularly well in the technical (33.75/41.25) and economic (15/16.25) criteria

groups. This performance may be attributed to its technical stability and reasonable operating costs, which are factors directly related to the relatively stable and controllable pollution characteristics of domestic wastewater type. However, limitations in by-product utilization and secondary emission control indicate that the system's environmental recovery potential and long-term sustainability remain constrained.

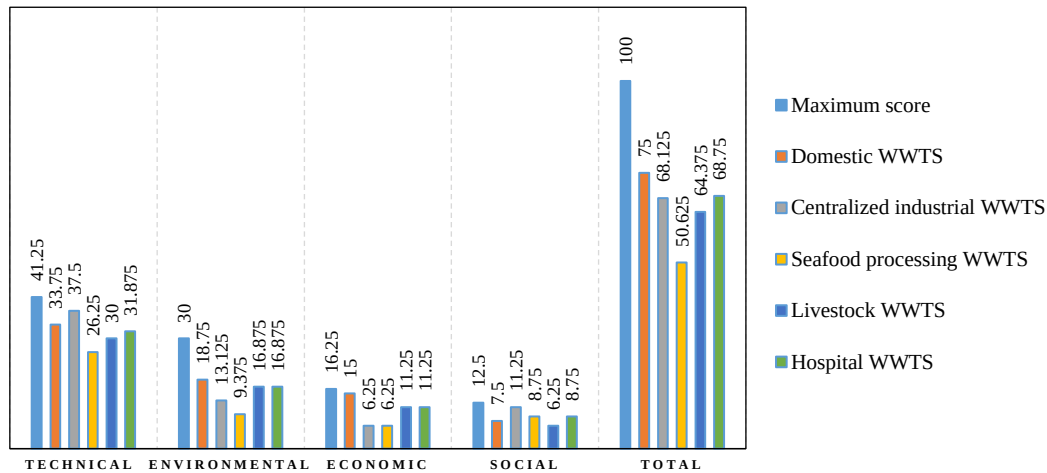


Figure 3. Quantified scores for the suitability assessment of WWTSs

Among the five wastewater types surveyed, the centralized industrial WWTS achieved a high score in the technical criteria group (37.5/41.25), indicating stable operation, ease of maintenance and compatibility with the skill level of the workforce. However, the environmental (13.125/30) and economic (6.25/16.25) criteria revealed existing issues related to high energy consumption, harmful gas emissions and limited potential for by-product recovery. Meanwhile, this system achieved the highest score in the social criteria group (11.25/12.5), reflecting its high adaptability to regional conditions and minimal impact on the community.

The seafood processing WWTS obtained the lowest overall score (50.625/100), with environmental and economic criteria at very low levels, 9.375/30 and 6.25/16.25, respectively. These results highlight the limitations of the currently applied technology in ensuring pollution control and cost efficiency. Although the social criteria reached an average level (8.75/12.5), low environmental and economic performance limits the overall sustainability of the system. This indicates the need for comprehensive technical and managerial interventions.

For the livestock and hospital WWTS, the total scores were 64.375 and 68.75, respectively. Both systems achieved relatively high technical scores (above 30/41.25) and reached the standards for effluent treatment efficiency. However, their economic performance was constrained by high capital, while environmental criteria were not fully met because of significant emissions of harmful gases, which are recognized as major contributors to climate change (IPCC, 2006) as well as high energy consumption. In particular, although the livestock WWTS demonstrated potential for by-product reuse, its low score in the social criteria group (6.25/12.5) reflected limitations related to aesthetics and negative community impacts.

In general, technical criteria dominated the evaluation, reflecting strong technical performance of the systems, whereas the lower weighting of environmental and economic criteria indicates unresolved sustainability issues in wastewater treatment in the study area.

3.4 Impact levels and priority for remediation of incidents in WWTSs

Based on the actual operating conditions of WWTS for the five wastewater types in the former Binh

Thuan Province, several types of operational incidents were identified and their impact levels assessed as follows: most systems experienced technical failures at varying degrees, predominantly ranging from minor to moderate, as shown in Figure 4.

In the five WWTS types surveyed, operational incidents were generally of minor to moderate severity (2.3-3.8 points), although recurrent technical issues were observed (Figure 4(a-1)-(e-1)). Domestic and livestock systems mainly faced aeration failures, sludge return problems and low biomass (Figure 4(a-1)-(d-1)), while seafood processing and centralized industrial systems were particularly affected by odor generation and sludge flotation (Figure 4(b-1)-(c-1)). Hospital systems exhibited sludge washout and oxygen deficiency resulting from malfunctioning pumps (Figure 4(e-1)). In all cases, remedial measures were rated as highly feasible (1-2 points), with priority actions focusing on aeration repair, pump replacement, sludge management and odor control (Figure 4(a-2)-(e-2)). Additional improvement options, such as installing

an anoxic tank (Figure 4(a-2)), were identified for improving nutrient removal (Le, 2007; Lam and Tran, 2015), though limited by space and cost. Overall, while the types and causes of incidents varied among systems, the findings consistently indicate that preventive maintenance and targeted technological upgrades are critical for sustaining treatment efficiency across WWTSs.

This is the first study to investigate operational incidents, assess their impact levels and propose priority rehabilitation measures for existing wastewater treatment systems in Binh Thuan area as well as in Vietnam. A review of operating wastewater treatment systems in the former Binh Thuan Province indicates that, although the issues are currently manageable, they pose potential risks to treatment efficiency if not addressed promptly. Among them, seafood processing and centralized industrial WWTS were identified as high-priority targets for rehabilitation due to their significant environmental impacts and effects on surrounding communities.

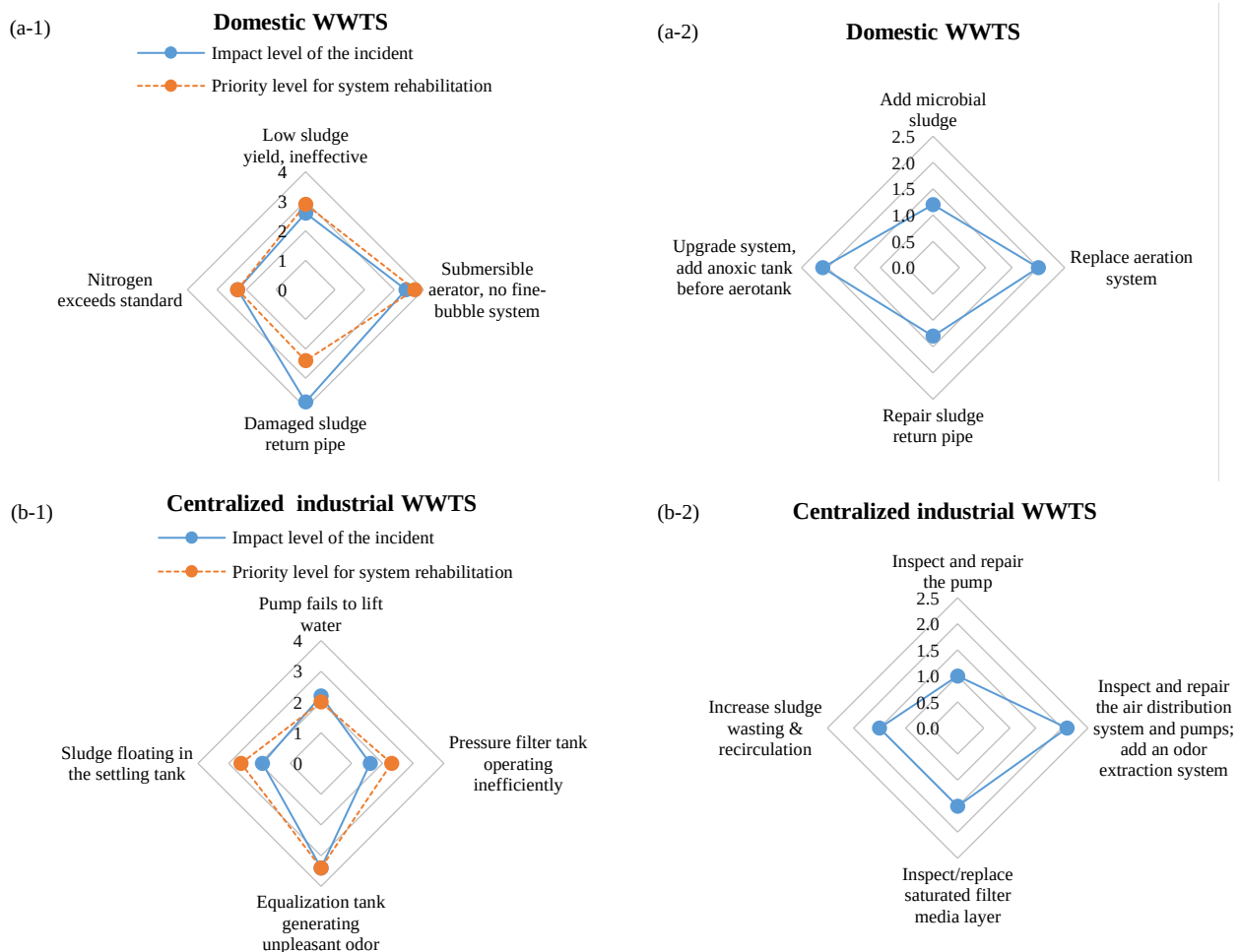


Figure 4. Impact level and renovation priority of incidents in wastewater treatment systems (a) Domestic wastewater, (b) Medical wastewater, (c) Livestock wastewater, (d) Seafood processing wastewater, (e) Centralized industrial wastewater (1) Incident impact level, (2) Renovation priority level

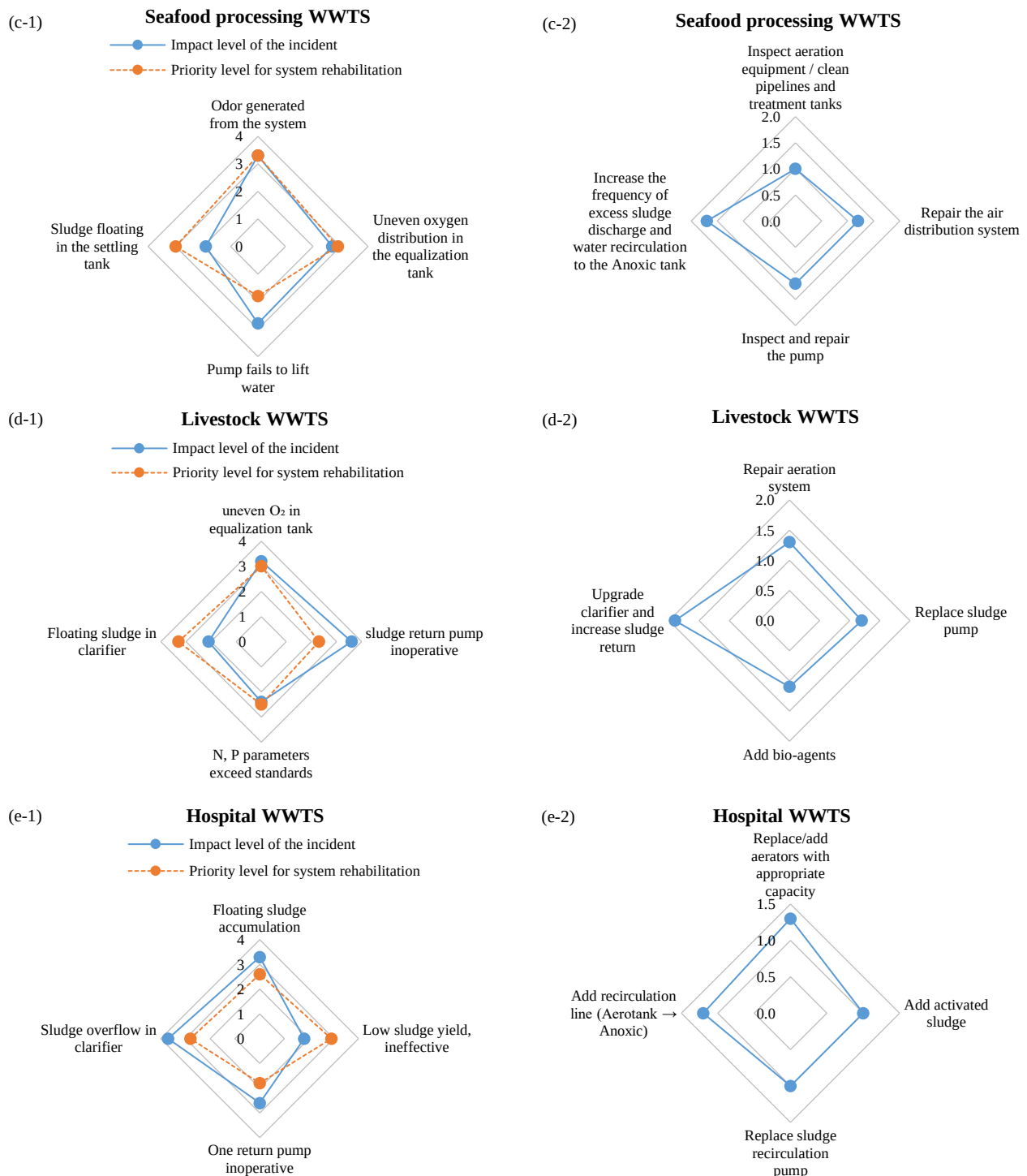


Figure 4. Impact level and renovation priority of incidents in wastewater treatment systems (a) domestic wastewater, (b) medical wastewater, (c) livestock wastewater, (d) seafood processing wastewater, (e) centralized industrial wastewater (1) incident impact level, (2) renovation priority level (cont.)

3.5 Incident localization and proposed technological improvements

Based on the survey and operational assessment of WWTs, the study identified critical locations within the treatment processes that are prone to operational

incidents and require priority improvement. Several key system components were therefore recommended for technological upgrading, with details summarized in [Table 4](#) and [Figure 5](#).

Table 4. Technical improvement solutions for the operation of WWTs

WWTSs	Notation, Process location identified for remediation or improvement	Proposed solution
Domestic (Figure 5(a))	TK2	Replace the aeration distribution system to ensure uniform oxygen supply.
		Add an anoxic tank upstream of the aerotank to enhance nitrogen and phosphorus removal efficiency.
	TK3	Supplement with activated sludge and repair/replace the return sludge system.
Centralized industrial (Figure 5(b))	TK2	Inspect and repair pumps and the aeration distribution system
	TK5	Increase both return sludge flow and excess sludge wasting frequency
	TK7	Replace the filter media
Seafood processing (Figure 5(c))	TK1	Conduct regular inspection and maintenance of pumps
	TK5	Inspect and improve the aeration system
	TK7	Increase the recirculation flow from the aerotank to the anoxic tank. Increase the frequency of excess sludge wasting
	TK8	Adjust sludge loading and add a sludge collection mechanism
Livestock (Figure 5(d))	TK3	Repair the aeration distribution system
	TK4	Add biological treatment agents
	TK6	Repair the sludge recirculation pump Increase the return sludge volume
Hospital (Figure 5(e))		Add an additional water recirculation line.
	TK4	Add activated sludge Replace the air blower with one of appropriate capacity
	TK5	Replace the sludge recirculation pump

(a) Domestic WWTs

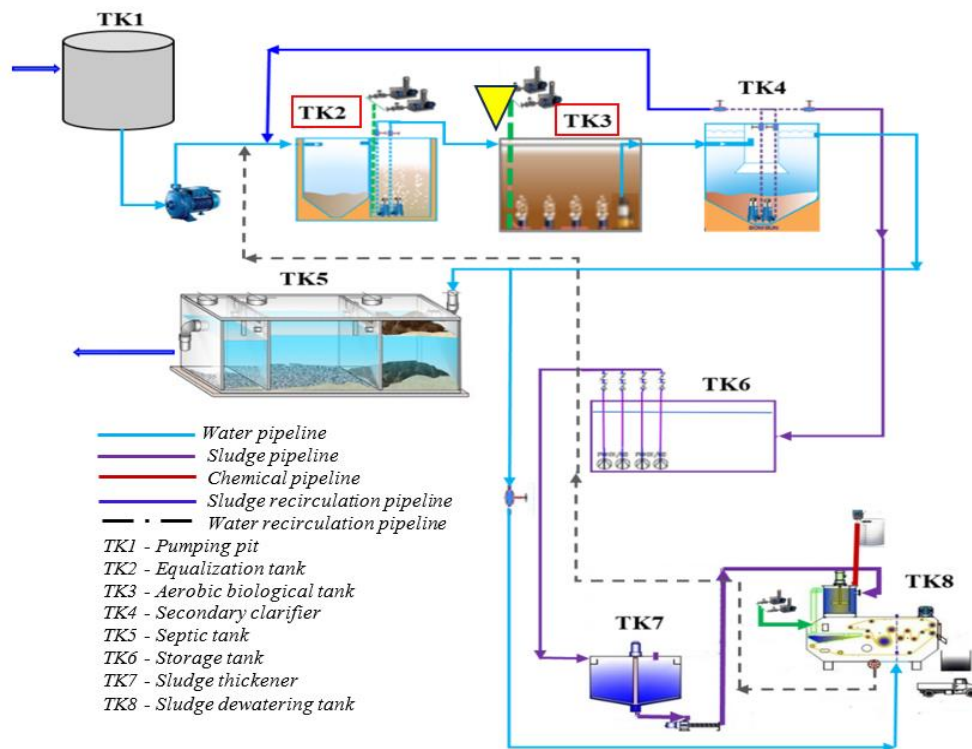
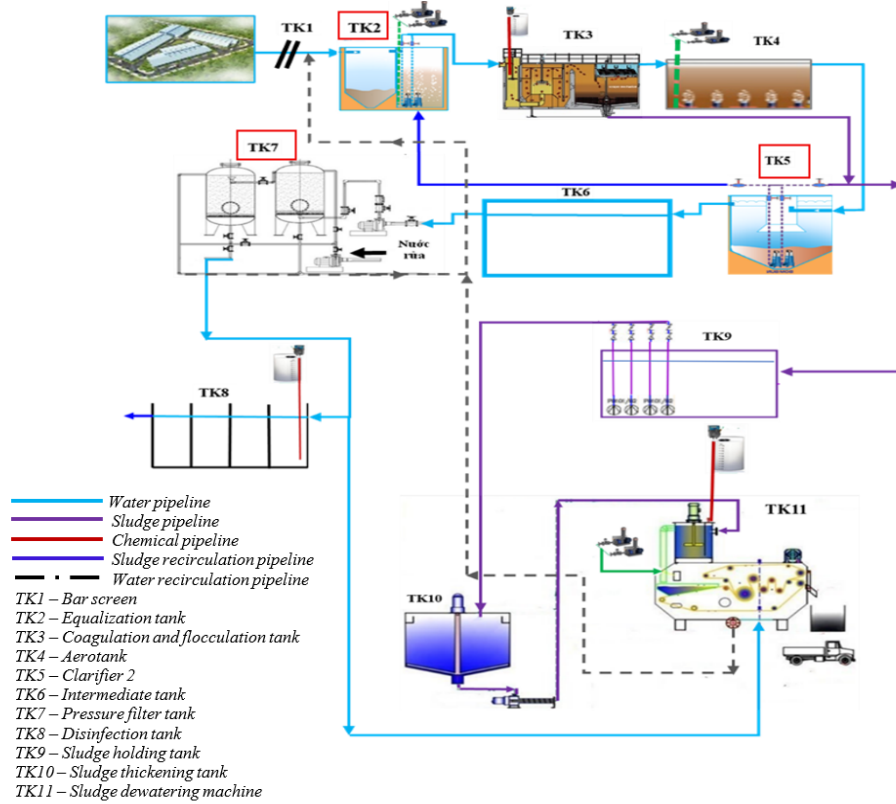


Figure 5. Wastewater treatment systems and solutions for troubleshooting

(b) Centralized industrial WWTS



(c) Seafood processing WWTS

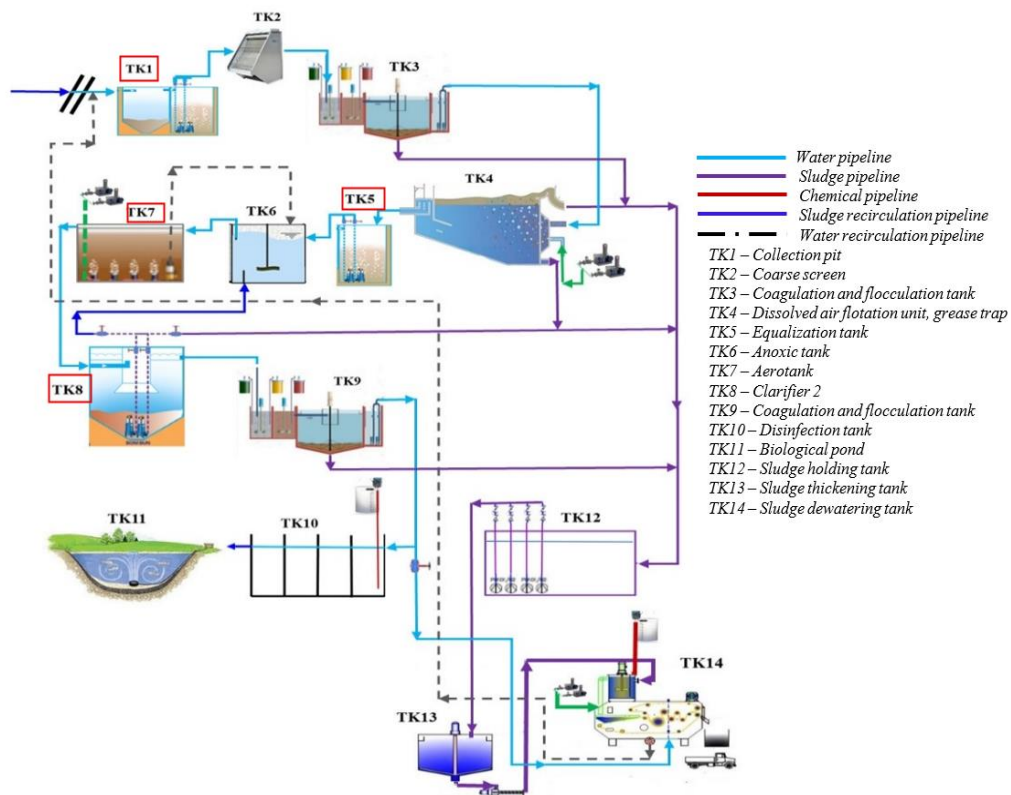
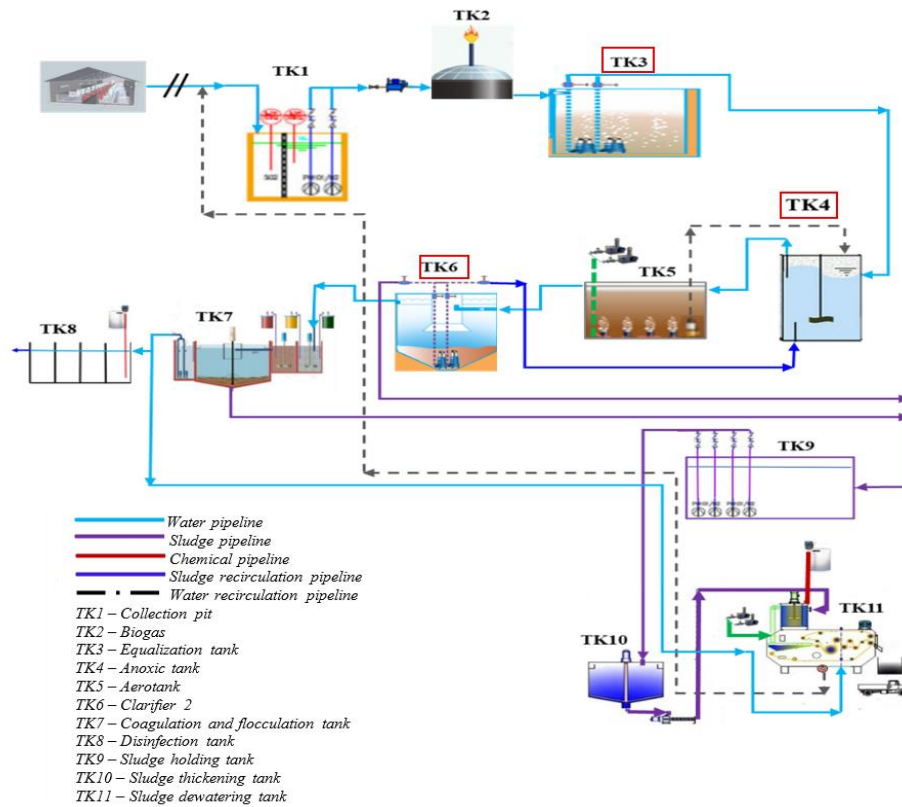


Figure 5. Wastewater treatment systems and solutions for troubleshooting (cont.)

(d) Livestock WWTS



(e) Hospital WWTS

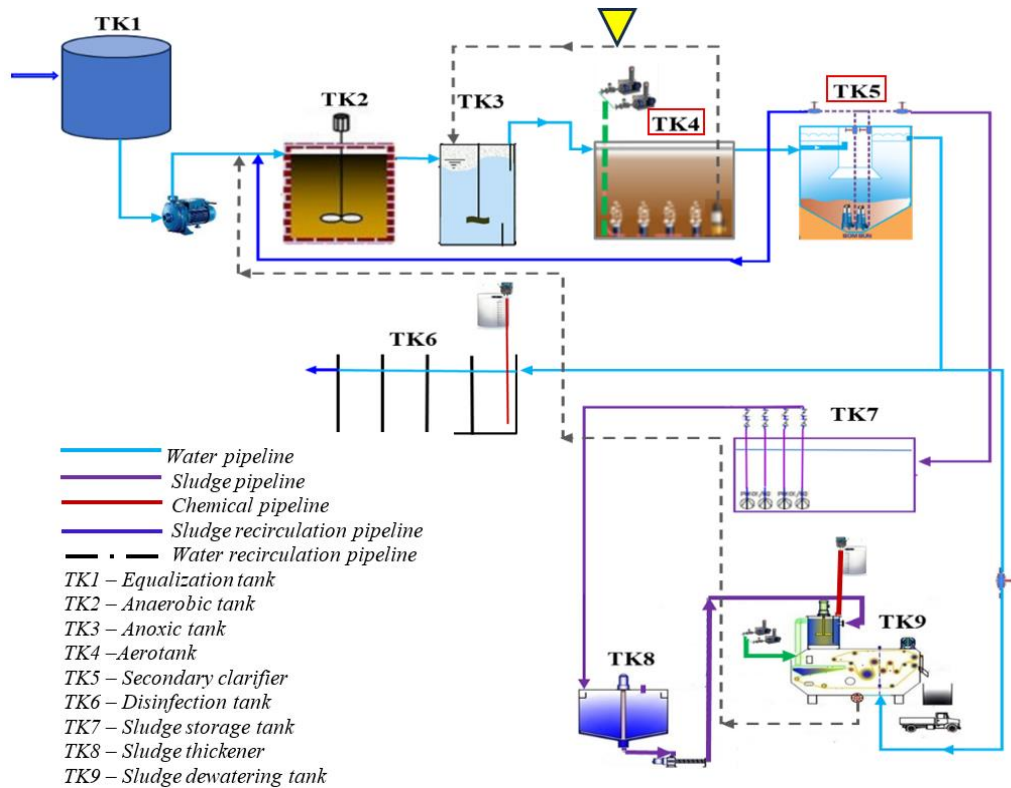


Figure 5. Wastewater treatment systems and solutions for troubleshooting (cont.)

4. CONCLUSION

This study represents the first application of a multi-criteria analysis (MCA) framework to systematically evaluate the suitability of existing wastewater treatment systems (WWTs) in the former Binh Thuan Province, Vietnam. Using 22 sub-criteria grouped into four sustainability dimensions, the assessment revealed that domestic and centralized industrial WWTs achieved the highest overall scores (75/100 and 73.1/100, respectively), reflecting stable technical performance and relatively balanced economic and social outcomes. In contrast, seafood processing WWTs obtained the lowest score (50.6/100), with particularly weak results in environmental (9.4/30) and economic (6.3/16.3) aspects, underscoring their high operational costs and unstable treatment efficiency. Livestock and hospital WWTs scored moderately (64.4/100 and 68.8/100), performing well in technical criteria but constrained by high energy consumption, gas emissions, and investment costs. Across all five systems, recurrent operational incidents, such as aeration failures, sludge flotation, and odor generation were identified, yet most had feasible technical remedies, with seafood processing and industrial systems prioritized for urgent rehabilitation due to their significant environmental and community impacts. These findings provide essential baseline data for selecting and adapting treatment technologies to local conditions, while offering a decision-support tool for regulatory agencies to enhance wastewater management and safeguard water resources in Vietnam's river basins. Further studies are strongly recommended to expand the MCA framework in order to better capture the long-term impacts of wastewater treatment technologies. In addition, applying this assessment framework to other regions and validating it through post-rehabilitation performance monitoring would enhance the applicability and reliability of the method.

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AUTHOR CONTRIBUTIONS

Conceptualization, H.P., T.T.M.H. and N.T.H.; Methodology, H.P., T.T.M.H. and N.T.H.; Validation, H.P.,

T.T.M.H. and N.T.H.; Formal Analysis, H.P., T.T.M.H.; Investigation, H.P., T.T.M.H.; Resources, H.P., T.T.M.H.; Data Curation, H.P., T.T.M.H.; Writing-Original Draft Preparation, H.P. and T.T.M.H.; Writing-Review and Editing, H.P., T.T.M.H. and N.T.H.; Visualization, H.P., T.T.M.H. and N.T.H.; Supervision, H.P.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Developing a Machine Learning Based Classification Model for Heavy Metal Contamination Levels in Mangrove Sediments

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ABSTRACT

Mangrove ecosystems play an important role in mitigating heavy metal pollution in coastal environments; however, direct assessment of their phytoremediation potential commonly relies on intensive field sampling and laboratory analyses. This study develops a machine learning-based prediction model to classify heavy metal contamination levels in mangrove sediments as a supporting tool for phytoremediation planning. A publicly available sediment dataset obtained from Kaggle, consisting of 300 samples with concentrations of Pb, Zn, Cr, Cu, and Ni, was used as a methodological testbed. Data preprocessing included feature normalization, label encoding, and class balancing using the Synthetic Minority Over-sampling Technique (SMOTE), followed by an 80:20 train-test split. Four classification algorithms Random Forest, Support Vector Machine (SVM), K-Nearest Neighbors (KNN), and XGBoost, were evaluated using accuracy, precision, recall, and F1-score metrics. Random Forest and SVM achieved the highest classification performance (92.5% accuracy), while KNN showed the lowest accuracy (81.5%). Feature importance analysis identified Cr, Pb, and Zn as the most influential variables in contamination level classification. Although the dataset is not site-specific and lacks ecological metadata, the results demonstrate the technical feasibility of machine learning models for sediment contamination classification. This study is positioned as a methodological proof-of-concept and highlights the need for future research integrating field-validated sediment data, mangrove species information, and biological uptake indicators to support robust phytoremediation assessments.

HIGHLIGHTS

- Machine learning predicts heavy metal contamination in mangrove sediment.
- Random Forest and SVM achieved the highest accuracy (92.5%).
- Cr, Pb, and Zn are key predictors of contamination levels.
- Results support ML as a tool for sediment contamination assessment.
- The study provides a proof-of-concept for ML in phytoremediation planning.

1. INTRODUCTION

1.1 Background

Heavy metal contamination in coastal ecosystems has been recognized as one of the most persistent and complex environmental threats over the past several decades (El-Sharkawy et al., 2025; Mok et al., 2023).apid expansion of industrial activities, maritime transport, aquaculture intensification, urban wastewater discharge, and mining operations has contributed substantially to the accumulation of toxic metals particularly Pb, Cr, Cd, Hg, and Zn in estuarine and coastal sediments (Kumari and Kumar, 2024;

Shaika et al., 2025). These contaminants tend to persist in benthic environments, disrupt nutrient cycling, impair microbial functions, and bioaccumulate in mangrove and seagrass food webs, ultimately posing severe ecological and human health risks through trophic transfer (John et al., 2022; Roy et al., 2023). As coastal areas in many developing countries, including Indonesia, experience accelerated anthropogenic pressures, the need for reliable, cost-effective, and scalable pollution assessment tools becomes increasingly urgent.

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Mangrove ecosystems are among the most critical coastal habitats affected by metal contamination, but they simultaneously play a key role in mitigating its impacts. Their specialized root systems pneumatophores, prop roots, and cable roots enhance sediment trapping, stabilize shorelines, and facilitate the accumulation and sequestration of metals through uptake, translocation, and immobilization mechanisms (Guo et al., 2025; Hossain et al., 2022). Several Indonesian mangrove species, such as *Avicennia alba*, *Rhizophora apiculata*, *Bruguiera gymnorhiza*, and *Sonneratia alba*, have been reported to display differential metal absorption abilities linked to their physiological traits, root anatomy, and biochemical tolerance pathways (Acharya et al., 2023; Akbar et al., 2026; Li et al., 2025). Despite these insights, current assessments of phytoremediation potential remain heavily dependent on laboratory-based analyses of sediments, roots, stems, and leaves procedures that involve destructive sampling, high operational costs, and long processing times (Bello et al., 2020; Sari and Soeprbowati, 2021). Such constraints limit the feasibility of routine monitoring across Indonesia's vast and heterogeneous mangrove landscapes.

Recent advances in environmental informatics have created opportunities to complement traditional laboratory analyses with computational, data-driven approaches. Machine learning (ML), in particular, has demonstrated strong capabilities in uncovering nonlinear relationships in ecological datasets, predicting environmental conditions, and reducing the time and cost associated with large-scale assessments (Chen et al., 2023; Drogkoula et al., 2023; Khruschew et al., 2022). ML has been effectively used for tasks such as seagrass habitat modeling, mangrove mapping from satellite imagery, coral species recognition, and pollution risk prediction (Gambin et al., 2021; Mederos-Barrera et al., 2025; Tallam et al., 2023). These successes suggest that ML may offer exploratory tools for preliminary classification or screening of phytoremediation-related indicators especially where field data are limited or difficult to collect.

However, despite its potential, the application of machine learning to mangrove phytoremediation remains underdeveloped. Existing ML studies on mangroves predominantly target species identification or habitat mapping using optical imagery, whereas phytoremediation research focuses on laboratory measurements without predictive modeling (Bacosa et al., 2025; Lan et al., 2024; Meraj et al., 2025; Zaka and Samat, 2024). To date, there is no integrated, validated

dataset linking mangrove morphometric or visual traits with sediment metal concentrations, particularly within Indonesian ecosystems. This gap significantly limits the development of data-driven phytoremediation assessment tools that are both scientifically grounded and ecologically meaningful.

In the absence of such field-based datasets, publicly available data sources, such as heavy metal datasets from open repositories and image datasets of mangrove species are sometimes used to explore methodological possibilities. However, these datasets often lack ecological connectivity, such as shared sampling locations, consistent metadata, or scientifically verified relationships between plant traits and sediment chemistry. For example, the heavy metal dataset used in this study originates from the Kaggle platform, which provides numerical contamination measurements but does not specify sampling coordinates, analytical protocols, or habitat context. Similarly, the mangrove image dataset consists of species-level photographs but does not include corresponding sediment measurements. These limitations pose substantial constraints on ecological interpretation and prevent the results from being generalized to real mangrove phytoremediation processes particularly in the Indonesian context where sediment composition, hydrodynamic regimes, and species distributions differ markedly across regions.

Given these considerations, the present study is positioned explicitly as a methodological exploration, aiming to evaluate the performance of several machine-learning algorithms in classifying contamination categories using numerical heavy-metal parameters from a non-field dataset. Rather than providing ecological assessments or management recommendations, this study seeks to (1) examine the classification behavior of ML models when applied to artificial or decoupled datasets; (2) identify computational patterns that may inform the design of future field-based data collection; and (3) critically discuss the scientific and ecological limitations of using non-validated data sources for phytoremediation modeling. By clarifying these limitations and highlighting the need for integrated sediment-vegetation datasets, this study contributes to ongoing efforts to develop scalable, data-driven tools for coastal pollution assessment while emphasizing the necessity of ecological validity and field verification in future research particularly for application in Indonesia's mangrove management and restoration programs.

Based on the above considerations, the objective of this study is to develop and evaluate a machine learning-based prediction model for classifying heavy metal contamination levels in mangrove sediments using numerical chemical parameters. Specifically, this study aims to (1) compare the classification performance of Random Forest, Support Vector Machine (SVM), K-Nearest Neighbors (KNN), and XGBoost models; (2) identify the most influential heavy metal variables contributing to contamination level classification; and (3) demonstrate the feasibility of machine learning approaches as a methodological support tool for phytoremediation planning rather than as a direct assessment of biological phytoremediation capacity. This study is explicitly positioned as a proof-of-concept and does not attempt to infer ecological or species-specific phytoremediation performance without field-validated datasets.

In this study, the term heavy metal contamination level refers strictly to categorical classifications derived from numerical sediment metal concentrations and does not represent direct ecological impact or biological uptake. The term phytoremediation planning is used conceptually to describe how sediment contamination classification may support preliminary decision-making regarding site prioritization, rather than to indicate measured phytoremediation performance. Species-level phytoremediation potential, which involves metal uptake, translocation, and tolerance mechanisms, is not directly assessed due to the absence of field-based biological data. Accordingly, all machine learning outputs in this study should be interpreted as computational classifications of sediment contamination patterns rather than as indicators of actual mangrove physiological responses or remediation effectiveness.

1.2 Definitions of key terms

To ensure clarity and consistency throughout this manuscript, key terms used in this study are defined as follows:

1. **Mangrove Phytoremediation Potential**-Refers to the inherent capacity of mangrove species to absorb, accumulate, or detoxify heavy metals and other pollutants from sediments or water. This term is specific to the evaluation of mangrove species' ability to remediate contaminated environments.

2. **Sediment Contamination Level**-Denotes the concentration of heavy metals or other pollutants

present in sediment samples. This is an environmental measurement and should not be conflated with the phytoremediation potential of mangrove species.

3. **Species Classification**-Refers to the identification and categorization of mangrove species based on morphological or image-based features. In this study, species classification is conducted as a separate task using a CNN-based model and is conceptually independent of heavy-metal analysis.

4. **Environmental Stress**-Indicates external pressures on mangrove ecosystems, such as salinity, pollution, or hydrological changes, that may affect species survival, growth, or remediation performance.

By explicitly defining these terms early in the manuscript and maintaining their consistent usage, the study avoids conceptual ambiguity between mangrove species traits, contamination measurements, and remediation potential.

2. METHODOLOGY

2.1 Data sources and provenance

This study utilized two publicly available datasets: (1) a sediment heavy-metal dataset obtained from the Kaggle open-data platform, and (2) an image dataset comprising 300 mangrove photographs representing three species classes. Importantly, these datasets originate from different sources, were collected independently, and are not ecologically linked. No field sampling, laboratory measurements, or paired sediment-vegetation data were conducted for this research.

Consequently, all analyses represent a methodological exploration of machine-learning behavior on non-integrated datasets, rather than an ecological assessment of phytoremediation potential. The heavy-metal dataset contains numerical concentrations of Pb, Cr, Cu, Ni, Zn, and related contamination categories. However, it lacks critical metadata, such as sampling coordinates, year of collection, sediment depth, analytical techniques (e.g., AAS, ICP-MS), and habitat context. These limitations constrain ecological interpretability and preclude using the dataset as a representation of mangrove sediments.

Similarly, the mangrove image dataset includes 300 images distributed across three species categories, stored in separate folders according to their class labels. These images are not associated with sediment conditions or metal measurements and thus cannot be used to infer phytoremediation capacity. Instead, the images were employed solely to develop a baseline

convolutional neural network (CNN) classifier for species-level categorization. By explicitly acknowledging these dataset limitations, this study maintains transparency regarding data provenance and highlights the methodological, rather than ecological, focus of the analyses.

2.2 Heavy-metal dataset preparation

Numerical preprocessing was applied to the heavy-metal dataset to support classification experiments. Categorical contamination labels were encoded using LabelEncoder, whereas numerical variables were normalized using MinMaxScaler to improve model convergence. Because the dataset exhibited class imbalance, the Synthetic Minority Over-Sampling Technique (SMOTE) was applied to the training subset to balance class distributions. SMOTE generates synthetic samples within feature space to reduce bias in supervised learning models (Elreedy et al., 2024; Wah et al., 2023). The dataset was split into training (80%) and testing (20%) subsets using a stratified approach to ensure proportional class representation. The machine-learning models trained on this dataset included Random Forest, Support Vector Machine, K-Nearest Neighbors, and XGBoost, selected based on their effectiveness in environmental classification tasks described in previous literature.

2.3 Image dataset collection and structure

The image dataset consists of 300 photographs representing three mangrove species categories. Images were arranged in folder-based class directories to support automated ingestion using the `image_dataset_from_directory()` function. This structure ensures consistent labeling and reproducible data loading across research runs. Because these images do not contain ecological or physiological indicators relevant to phytoremediation (e.g., root morphology, tissue metal content), the image dataset was used solely for species classification, not for predicting heavy-metal uptake. This distinction addresses reviewer comments concerning ecological invalidity.

2.4 Image preprocessing

Standard image preprocessing was conducted before training the CNN. All images were resized to 224×224 pixels to conform to the model input layer. Pixel values were normalized to a 0-1 scale to improve model training stability and convergence efficiency. No data augmentation was performed beyond

normalization because the objective was methodological demonstration rather than ecological generalization. The dataset was split into training and validation subsets using a ratio of 80:20, managed through the built-in TensorFlow parameter `validation_split=0.2`.

2.5 CNN model architecture

The CNN architecture consisted of three convolutional blocks with 32, 64, and 128 filters, each followed by MaxPooling layers to reduce spatial dimensionality. The extracted feature maps were then flattened and connected to a dense layer with 128 neurons, followed by a final dense layer with three softmax units representing the species classes. This architecture is commonly used in small-scale ecological image classification studies (Jongjaraunsuk et al., 2024; Maruf et al., 2024; Reshma et al., 2023; Yuan and Lin, 2021), and the model contained a total of 11,169,347 trainable parameters.

It is important to emphasize that this CNN experiment was conducted solely for species classification and not for inferring phytoremediation potential, as no feature or label in this dataset relates to heavy-metal accumulation. Therefore, the CNN experiment should be considered a stand-alone demonstration of species classification, separate from the heavy-metal analysis described elsewhere in this study.

2.6 Model training

The CNN was trained using the Adam optimizer, categorical cross-entropy loss, batch size of 32, and a variable number of epochs until validation performance stabilized. Early stopping and learning-rate scheduling were available to prevent overfitting but were used only as auxiliary monitoring tools. The heavy-metal classification models (RF, SVM, KNN, XGBoost) were trained using Scikit-learn with hyperparameters tuned through grid search.

2.7 Model evaluation

Evaluation metrics included accuracy, weighted precision, weighted recall, and weighted F1-score, in accordance with established machine-learning evaluation practices. Confusion matrices were used to examine class-level performance and misclassification patterns. Evaluation was performed separately for (1) the CNN species classifier, and (2) the numerical heavy-metal classifiers. No cross-dataset integration or ecological inference was conducted.

3. RESULTS

3.1 Dataset characteristics and environmental context

The sediment dataset obtained from Kaggle consists of eight heavy metal parameters (Ni, Pb, Cr, Hg, Cd, As, Cu, and Zn), which were categorized into three contamination levels (low, moderate, and high) based on percentile thresholds of the dataset distribution. Specifically, concentrations below the 33rd percentile were classified as low contamination, values between the 33rd and 66th percentiles as moderate contamination, and values above the 66th percentile as high contamination. This data-driven stratification allows the machine learning models to learn relative contamination gradients rather than absolute regulatory exceedance (Carrillo et al., 2022; Crane et al., 2021).

To evaluate the severity of these contamination levels, the high contamination class was qualitatively compared with Indonesian sediment and environmental quality guidelines reported in previous studies and national regulations. Several metals, particularly Pb, Cd, Hg, and Cr, exhibit concentration ranges in the upper contamination class that are comparable to or exceed commonly reported threshold values for coastal sediments in Indonesia. These metals are frequently associated with industrial discharge, port activities, and urban runoff in mangrove-dominated coastal zones. Therefore, while the dataset is not site-specific to Indonesian mangroves, the upper contamination category can be interpreted as representing environmentally stressful conditions relevant to Indonesian coastal ecosystems.

3.2 Preprocessing and class structure improvement

The raw dataset exhibited class imbalance, particularly in the High contamination category. After SMOTE application, the balanced dataset displayed improved separation among classes in the PCA space. Although PCA is not used for model training, the emerging class clusters reflect that each contamination category possesses distinguishable metal profiles. From an ecological perspective, this separation aligns with known shifts in sediment chemistry, where elevated Pb, Zn, and Cr often indicate more degraded coastal environments, while low metal profiles typically correspond to minimally disturbed mangrove stands. Normalization further enhanced feature comparability, ensuring that metals with inherently

larger magnitude (e.g., Zn) did not overshadow metals with lower environmental concentration (e.g., Hg, Cd). This step is ecologically relevant because metal toxicity thresholds for mangroves depend on relative not absolute concentration differences.

Based on the Principal Component Analysis (PCA) results, two principal components (PC1 and PC2) were used to represent the largest variation in the heavy metal features, as shown in Figure 1. The first component (PC1) captures the greatest variance distribution, which is largely influenced by highly correlated heavy metal parameters, while the second component (PC2) describes additional variation not accounted for by PC1. Visually, the scatter plot in Figure 1 shows a fairly clear separation pattern between classes, indicating that the data structure is well organized after class balancing using SMOTE. This PCA was not used for model training but served as an exploratory tool to ensure that the preprocessing produced well-distributed data ready for the classification stage.

3.3 Training performance of CNN-based image classification

The CNN trained on 300 mangrove images achieved a validation accuracy of approximately 92%. The learning curves demonstrate stable convergence without overfitting. However, the model exhibited inconsistent performance across classes; the Moderate contamination class obtained the highest F1-score (0.95), whereas the High class scored the lowest (0.29). From an ecological viewpoint, such inconsistency is expected because moderate stress in mangroves often manifests as distinct morphological cues (leaf yellowing, reduced canopy density) that are easier for the model to learn. In contrast, high levels of heavy-metal stress may produce heterogeneous visual symptoms or may not be visually distinguishable at all, reducing classification accuracy.

The model training performance is illustrated in Figure 2, which presents the training and validation accuracy and loss curves. Both accuracy curves show a consistent upward trend, while the loss curves decrease steadily across epochs, indicating effective learning behavior. The close alignment between training and validation performance suggests that the model does not suffer from significant overfitting and maintains good generalization capability.

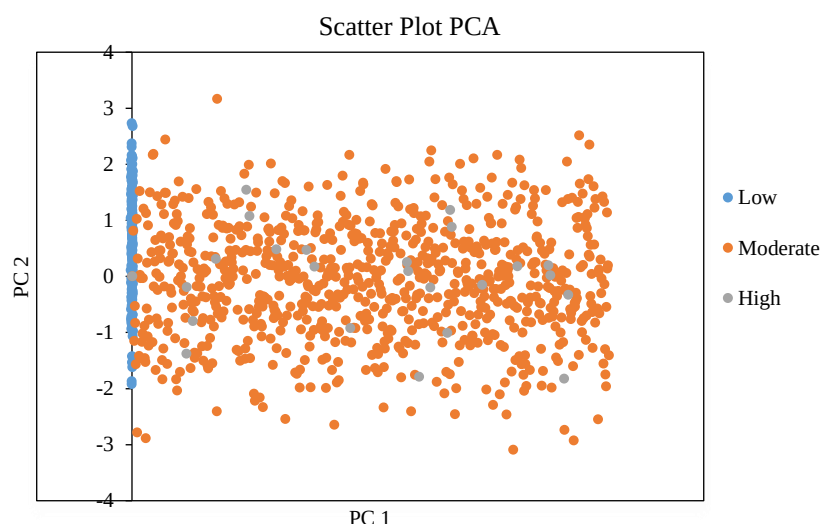


Figure 1. PCA scatter plot for class separation of phytoremediation potential

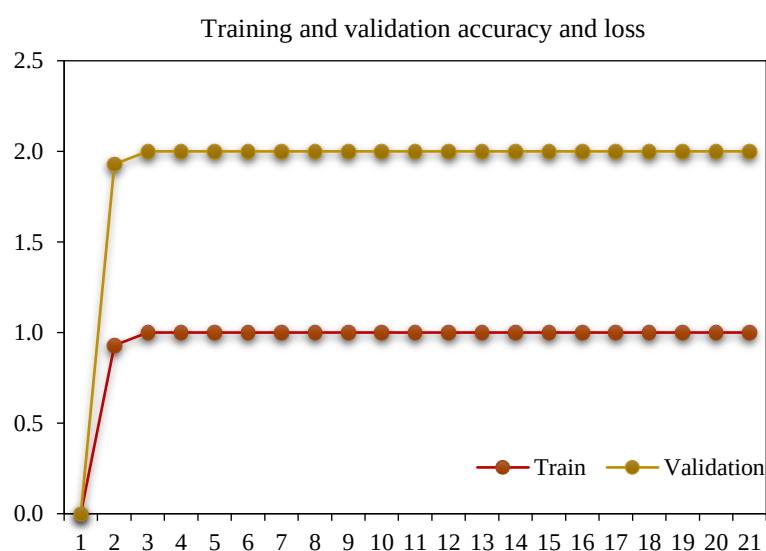


Figure 2. Training and validation accuracy and loss curves of the XGBoost model

3.4 Performance of machine-learning models for sediment classification

This section presents the performance of the mangrove phytoremediation potential classification model based on several algorithms used, namely Random Forest, SVM, KNN, and XGBoost. Evaluation was conducted using accuracy, precision, recall, F1-score metrics, as well as confusion matrix analysis to observe per-class performance (Low, Moderate, High).

The structured sediment dataset was evaluated using Random Forest, SVM, KNN, and XGBoost, and the comparative performance of these models is summarized in Table 1. XGBoost achieved the highest overall performance, with an accuracy of 0.930 and an

F1-score of 0.933, followed closely by SVM and Random Forest, which exhibited comparable accuracy values of 0.925. The stronger performance of tree-based ensemble models aligns with ecological expectations, as heavy-metal contamination data often exhibit nonlinear interactions and threshold responses, conditions under which ensemble learning methods typically outperform distance-based classifiers such as KNN.

Further examination of the best-performing XGBoost model using a confusion matrix revealed that misclassifications most frequently occurred between the Moderate and High contamination categories. Ecologically, this pattern reflects the overlapping concentration ranges of Pb and Zn in

moderately and severely impacted estuarine environments, where the absence of species-specific metal uptake data complicates precise discrimination

of contamination severity. The confusion matrix of the best-performing XGBoost model is shown in Figure 3.

Table 1. Performance comparison of machine learning models based on accuracy, precision, recall, and F1-score

Model	Accuracy	Precision	Recall	F1-score
Random Forest	0.925	0.926	0.925	0.925
SVM	0.925	0.939	0.925	0.928
KNN	0.815	0.883	0.815	0.812
XGBoost	0.930	0.940	0.930	0.933

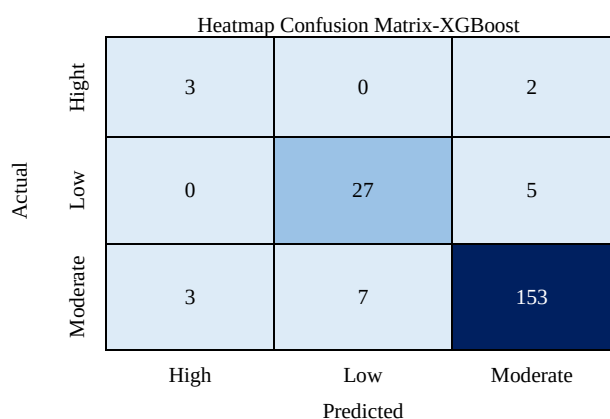


Figure 3. Heatmap of the XGBoost Model confusion matrix

3.5 Environmental interpretation of feature importance

The feature-importance analysis identifies Zn (0.35), Pb (0.35), and Ni (0.10) as the dominant predictors. These results are consistent with environmental reports indicating that Zn and Pb are among the most mobile and bioavailable metals in tropical coastal sediments. Moreover:

1) Zn plays a dual ecological role essential at low concentrations yet phytotoxic at high exposure levels. Its high importance suggests it is a sensitive indicator of sediment quality variation.

2) Pb, widely documented in Indonesian coastal areas due to port activities and fuel combustion, exhibits long-term persistence and strong affinity to fine sediments typically found around mangrove roots.

3) Ni ranking third aligns with its known toxicity to mangrove seedlings, often causing chlorosis and reduced root biomass.

Although the dataset is not mangrove-derived, the ranking of important metals follows ecologically plausible patterns, reinforcing the environmental coherence of the ML findings.

3.6 Decision boundary and ecological interpretability

The PCA-based decision boundary visualization demonstrates that Low contamination areas exhibit well-defined separation, whereas Moderate and High clusters show overlaps. These overlaps mirror real-world sediment conditions where metal concentrations may fluctuate seasonally or spatially within mangrove stands due to tidal resuspension, sediment deposition, and organic matter interaction.

This reinforces that sediment contamination exists on a continuum, making strict categorical boundaries ecologically unrealistic, yet machine learning models can still approximate broad contamination trends. The decision boundary plot shown in Figure 4 illustrates how the XGBoost model separates phytoremediation potential classes despite partial feature overlap.

3.7 Complementary evaluation: ROC curves and learning dynamics

The ROC curves, as shown in Figure 5, indicate that the Moderate class achieved the highest discriminability, consistent with clearer ecological signals at intermediate contamination levels. Meanwhile, the High class ROC indicates weaker sensitivity, reflecting the noisier and less predictable nature of severe pollution events in real sediment systems. The learning curve analysis further confirms that the model benefits from additional training data, a typical outcome in environmental datasets characterized by high variability.

The per-class ROC curves indicate strong discriminative performance for the Low and Moderate contamination classes, while slightly reduced performance is observed for the High class due to the limited sample size. The learning curve demonstrates stable training and validation performance as the dataset size increases, suggesting that the model does not suffer from significant overfitting and is well optimized for the available data.

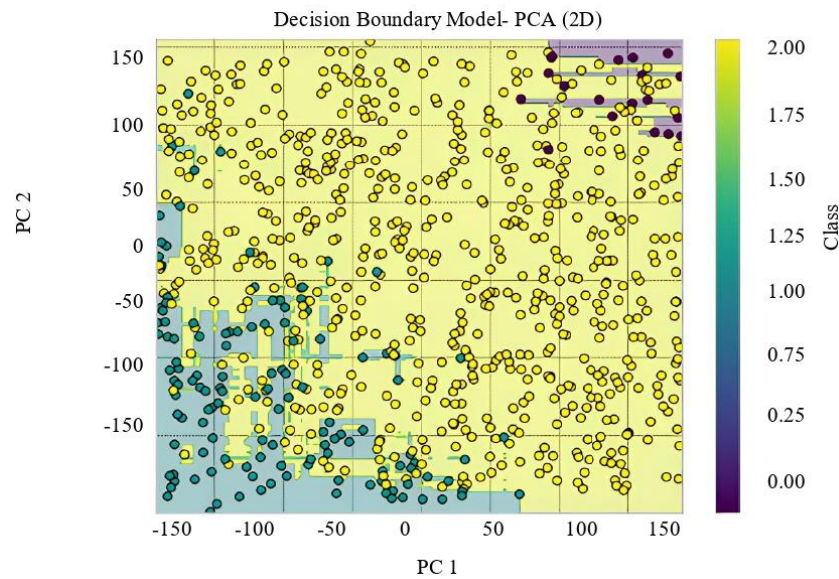


Figure 4. Decision boundary plot

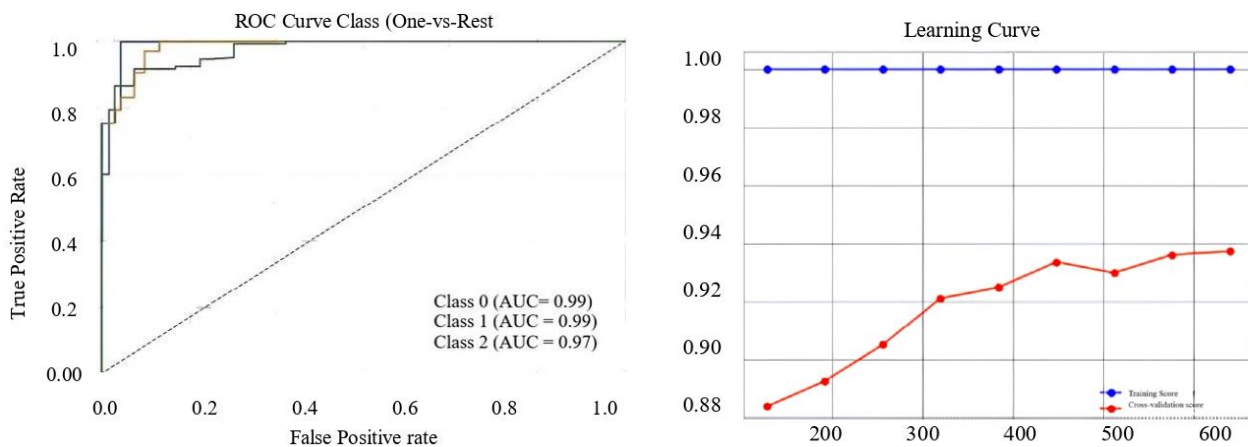


Figure 5. presents the ROC curves and learning curves of the XGBoost model

4. DISCUSSION

The results of this study indicate that the XGBoost model is capable of delivering excellent classification performance in distinguishing mangrove phytoremediation potential based on heavy metal parameters in sediments. The model achieved an accuracy of 92%, indicating that most predictions matched the true labels. The confusion matrix revealed that the Moderate class was the easiest for the model to recognize, likely due to its larger sample size, resulting in more stable data patterns. Conversely, the High class exhibited the highest error rate due to its relatively small sample size. Feature importance analysis showed that Zn (0.354), Pb (0.349), and Ni (0.104) were the most influential factors in determining phytoremediation potential classification, highlighting that these metals play a key role in

differentiating phytoremediation capability at the study sites.

Compared to baseline models such as Random Forest, SVM, and KNN, XGBoost remained the most stable and accurate model. Random Forest and SVM had competitive accuracy but slightly lower, whereas KNN showed the lowest performance, particularly on datasets with imbalanced class distributions. This reinforces that XGBoost is more suitable for handling non-linear and complex data structures like sediment heavy metal parameters. Additional visualizations, such as the decision boundary, showed that the model could separate classes relatively clearly in the reduced feature space, although overlap still appeared, especially for the High class. Meanwhile, per-class ROC curves indicated good discriminative ability for the Low and Moderate classes but slightly decreased performance for the High class due to limited data.

The learning curve suggested that the model did not experience significant overfitting; performance remained stable as data size increased, indicating that the model was sufficiently optimized for the available dataset.

Previous studies largely focused on traditional statistical analyses or manual classification to assess mangrove phytoremediation potential. For example, (Akbar et al., 2026; Alotaibi et al., 2025; Yap and Al-Mutairi, 2023) used linear regression to predict heavy metal accumulation in mangrove roots, while (Hassan et al., 2025; Koudenoukpo et al., 2021; Petrea et al., 2020; Wong et al., 2021) grouped mangrove species based on bioaccumulation indices using a descriptive approach without automated predictive models. Such approaches have limitations, especially when relationships between variables are non-linear or when the number of environmental parameters is large. Compared to these studies, the use of machine learning (XGBoost) in this study offers significant improvements by handling large datasets, identifying complex patterns, and increasing overall classification accuracy. Therefore, this study contributes new insights to mangrove ecology by providing a modern, high-precision predictive approach.

Additionally, the use of several baseline models such as Logistic Regression, SVM, KNN, and Random Forest showed that XGBoost outperformed them in classification performance (Devan and Khare, 2020; Gündoğdu, 2023; Hamidou and Mehdi, 2025; Kavzoglu and Teke, 2022; Shahri et al., 2021). Logistic Regression achieved high accuracy but struggled with non-linear relationships, whereas SVM and KNN were sensitive to feature scale and distribution (Khatun et al., 2025; Sannigrahi and Thandeeswaran, 2024; Sarwar et al., 2024). Random Forest performed reasonably well but still lagged behind XGBoost, which benefits from iterative boosting to gradually correct errors (Alharbi, 2025; Imani et al., 2025; Khatun et al., 2025; Natras et al., 2022). This comparison reinforces that XGBoost is the most suitable model for classifying phytoremediation potential based on sediment and vegetation parameters.

With its high and consistent performance, the results of this study can support the identification of coastal rehabilitation sites, determine the most effective mangrove species for phytoremediation, and enable automated environmental quality monitoring. A key advantage of a machine learning-based approach is that it can be updated easily when new

data becomes available, functioning as an adaptive decision support system. Future research can expand the model by incorporating additional features such as drone imagery, NDVI, mangrove biomass, or hydrological conditions to develop a more comprehensive predictive model.

To achieve a true classification of mangrove species based on phytoremediation potential, future studies must integrate sediment contamination data with species-specific biological and physiological measurements. Field-based datasets should be collected from mangrove sites with known species composition, where both sediment heavy metal concentrations and plant tissue samples (roots, stems, and leaves) are analyzed. Phytoremediation capacity can then be quantified using established indices such as bioconcentration factor (BCF), translocation factor (TF), and bioaccumulation factor (BAF), which provide mechanistic links between sediment contamination and plant uptake behavior.

Different phytoremediation mechanisms can be explicitly modeled by linking heavy metal distributions to dominant biological processes. Phytoextraction can be represented by high metal accumulation in aboveground biomass combined with elevated TF values, phytostabilization by high root metal retention with low translocation, and phytodegradation or rhizoremediation by strong associations between metal concentrations and rhizosphere microbial activity. By incorporating these mechanistic indicators as target labels or auxiliary features, machine learning models could move beyond sediment-based contamination classification toward biologically meaningful predictions of species-level phytoremediation strategies. Such an integrated framework would enable a more ecologically grounded and interpretable classification of mangrove species phytoremediation potential.

Nevertheless, this study has limitations, particularly due to the imbalanced class distribution, which caused suboptimal performance for the High class. The limited number of features (restricted to metal elements) also constrained the depth of information the model could learn. In the future, accuracy and generalization could be improved by increasing the dataset size, adding a variety of biophysical parameters, and balancing sample sizes across classes. Integrating other data sources, such as drone imagery or vegetation parameters, could further strengthen the model in mapping mangrove phytoremediation potential more comprehensively.

5. CONCLUSION

This study aimed to evaluate whether machine-learning models particularly XGBoost can classify sediment contamination levels based on heavy-metal parameters. The results demonstrate that XGBoost achieved the strongest predictive performance among the tested algorithms, with an accuracy of 0.93 and consistently high precision and F1-scores. These findings indicate that boosting-based models are effective in capturing nonlinear relationships and co-variation among metals such as Zn, Pb, and Ni, which emerged as the most influential predictors. Although derived from a non mangrove-specific dataset, the identified metal patterns align with widely reported contamination profiles in tropical coastal environments.

However, the results should be interpreted within the methodological constraints of this study. The sediment dataset originates from a general-purpose online repository and is not ecologically linked to the mangrove images used for the parallel CNN experiment. Consequently, the current model cannot be used to infer actual phytoremediation capacity or species-specific metal uptake in real ecosystems. In addition, the High contamination class remains poorly represented, limiting the model's ability to generalize across the entire pollution gradient. These limitations highlight the need for field-based sediment sampling, species-level validation, and integration of biologically grounded indicators of mangrove stress.

Despite these constraints, the study provides a methodological foundation for future applications of machine learning in coastal environmental assessment. The consistent classification patterns suggest that ML can support early screening of contamination hotspots, prioritize locations for field monitoring, and complement traditional laboratory-based analyses. Future research should incorporate site-specific sediment profiles, mangrove physiological measurements, and spatial data, such as UAV imagery or LiDAR to develop ecologically robust models that can inform restoration planning, identify areas at risk, and strengthen decision-making in coastal ecosystem management.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing original draft preparation, Writing, review and editing: Harry Irawan Johari. The author has read and agreed to the published version of the manuscript.

DECLARATION OF CONFLICT OF INTEREST

The author declares no conflict of interest.

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Growth Responses and Phytoremediation Capacity of *Colocasia esculenta* under Drought Conditions in Pb-Contaminated Soil

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ABSTRACT

Phytoremediation is an effective, plant-based strategy for removing heavy metals from contaminated environments under various conditions. This study examines how lead (Pb) pollution and drought stress affect *Colocasia esculenta*'s physiological reactions and capacity to accumulate Pb. Plants were grown for 45 days under two soil moisture conditions (100% and 50% field capacity) and treated with 100 mg/kg Pb. The findings indicated that drought stress significantly diminished root growth, whereas Pb exposure exhibited no significant effect ($p > 0.05$). No significant differences were observed in stem height, dry plant biomass, and relative growth rate (RGR) values ($p > 0.05$). Under the combined Pb exposure and drought condition, the chlorophyll content and chlorophyll fluorescence parameters (PI and Fv/Fm) did not change. Under drought conditions, translocation factor (TF) levels were less than 1 (0.45-0.56) for the first 30 days; yet, following 45 days, they were more than 1 (1.17). Under drought stress, the bioaccumulation factor (BAF) values were over 1 (1.99-5.14), suggesting a high potential for Pb accumulation. All of these indicate that *C. esculenta* is resistant to Pb and has the capacity to phytoremediate Pb-contaminated dry soils.

HIGHLIGHTS

- *Colocasia esculenta* was assessed for Pb phytoextraction under drought conditions.
- A 45-day pot experiment mixed 100 mg/kg of Pb with two levels of soil moisture.
- Drought impeded root development, but Pb alone had no significant effect on growth.
- Chlorophyll, Fv/Fm, and PI demonstrated stability under drought and Pb stress.
- BAF remained above 1; TF increased to 1.17 by day 45 during drought conditions.

1. INTRODUCTION

Lead (Pb) is classified as a hazardous heavy metal because of its severe toxicity and environmental persistence, making it a major environmental pollutant of global concern (Qi et al., 2018). Pb poisoning in agricultural soils is frequently caused by long-term farming practices, industrial emissions, or excessive pesticide use. This poses serious risks to crop output, soil quality, and human health (Kumar et al., 2020; Rahman et al., 2024). Pb pollution in agricultural areas has become an increasingly serious environmental problem in Thailand. For example, industrial activities

in Rayong Province have resulted in Pb accumulation in soils and crops, with some fruit samples containing Pb levels exceeding the national safety limit of 1 mg/kg for food crops, according to the Ministry of Public Health Announcement, while vegetable cultivation in Phitsanulok Province has been reported to contain Pb concentrations up to 8.29 mg/kg (Apilux et al., 2023). This contamination puts food safety at risk and pinpoints how urgently sustainable soil remediation techniques are needed.

Phytoremediation is one of the remediation strategies that has drawn the most attention as a

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sustainable, economical, and ecologically friendly way to reduce heavy metal contamination. This plant-based method takes advantage of some species' innate ability to absorb, store, and fix hazardous metals from polluted soils in both controlled and field settings (Jabeen et al., 2009). Even though phytoremediation is a promising and eco-friendly method, inorganic limitations like drought or water scarcity can restrict plant growth and biomass production, which lowers pollutant uptake and remediation efficiency (Tangahu et al., 2011). Seasonal drought, especially in the summer months, can limit the effectiveness of phytoremediation in soils contaminated with heavy metals. Plants under drought stress undergo complex physiological and biochemical changes, such as osmotic imbalance and decreased biomass (Ozturk et al., 2021). Therefore, choosing the right plant species for metal extraction and cleanup requires drought tolerance (Qi et al., 2018).

Some drought-resistant species, like Bermuda grass (*Cynodon dactylon*) (Sekabira et al., 2011) and shrub violet (*Hybanthus floribundus*) (Kachenko et al., 2011), exhibit the ability to accumulate heavy metals; nevertheless, their restricted biomass and slow growth limit extensive utilization. Finding new plant species with higher biomass output, drought tolerance, and the ability to accumulate metals is therefore crucial for phytoremediation research (Sarma, 2011). Pb-contaminated soils usually have seasonal water constraints, such as droughts or inconsistent rainfall, which restrict plant development. Since phytoremediation efficacy depends on plant biomass production and transpiration-driven mass flow, prospective species must be assessed under metal and water deficiency conditions, not just single-stress conditions. In tropical and subtropical regions, *Colocasia esculenta* (L.) Schott belongs to the family Araceae and is a wetland plant that has demonstrated tolerance to environmental stress and a notable ability to absorb heavy metals in both roots and shoots (Davis et al., 2023; Mariwy et al., 2024). However, little is known about how drought stress affects *C. esculenta*'s photochemical efficiency and capacity for Pb accumulation. This study aims to examine the drought tolerance, photosynthetic efficacy, and phytoremediation capabilities of *C. esculenta* in Pb-contaminated soil under controlled soil-moisture regimes (100% and 50% pot capacity) to develop recommendations for sustainable soil management and phytoremediation in drought-affected agricultural areas of Thailand.

2. METHODOLOGY

2.1 Plant, soil material, and experimental design

Colocasia esculenta was obtained from regions without a history of contamination near Mae Tao Creek, Phra That Pha Daeng Subdistrict, Tak Province, Northern Thailand. To ensure constant growth, plants were cultivated in a greenhouse for a month on soil completely devoid of heavy metals before the experiment. Uniform plants of similar size were chosen for the experiment; each had an average shoot length of around 21-23 cm and a root length of about 10 cm. Soil with a low background Pb concentration (<11 mg/kg) and no fertilizer amendment was obtained from Chatuchak Market, Bangkok, Thailand (Table 1). Soaking the soil in water allowed for the determination of the pot's field capacity (PC). The water was drained for a whole day after the plastic pots were covered with plastic sheets. By subtracting the dry weight of the soil from the weight of the soil after draining, the water content in PC was determined (Khamsuk et al., 2018). To achieve 100% PC and 50% PC, 930 mL and 465 mL of water were added to the pots; an initial assessment revealed that plants endured at 50% PC, establishing the maximum drought level they can withstand. The plants were relocated into plastic pots filled with soil at 100% PC and 50% PC. The pots were covered with plastic sheets to stop evaporation. By monitoring the overall weight of the pots on day 0, the water level in the pots was maintained throughout the 45-day experiment. After that, the weight was noted every day, and water was added to return the entire weight to its starting point. Additionally, moisture levels were regulated; the 50% PC treatment was maintained at a gravimetric soil water content of 24% (w/w), whereas the 100% PC treatment was maintained at 48% (w/w).

To achieve Pb contamination, 100 mg/kg of dry soil containing lead carbonate (PbCO_3) was added to the homogenized soil. The experimental conditions included (1) soil moisture, comprising two levels (100% and 50% PC), and (2) Pb addition, consisting of two levels (0 and 100 mg/kg). The pot experiment was arranged in 4 treatments: 0 mg/kg Pb with 100% PC (T1; control), 0 mg/kg Pb with 50% PC (T2; drought), 100 mg/kg Pb with 100% PC (T3; Pb + no drought), and 100 mg/kg Pb with 50% PC (T4; Pb + drought). Three repetitions of each treatment were conducted, with one plant per pot serving as a duplicate. The experiment was conducted using a fully

randomized approach. Plants were grown in the greenhouse under normal natural environment conditions for 45 days (28-32°C, 60% humidity, natural sunshine, and a 12/12 h photoperiod). During the trial period, all clearly visible symptoms of drought, such as wilting, leaf rolling, loss of turgor, leaf drooping, and margin drying or browning, as well as Pb-toxicity symptoms, such as chlorosis, necrotic lesions, and stunting or decreased leaf size in the plants, were documented. Plant growth and Pb accumulation were measured after 30 and 45 days, and the performance index (PI) and photosynthetic pigments were evaluated at the end of the experiment.

2.2 Growth measurement

Plant samples were gathered, cleaned twice with tap water, rinsed with distilled water, and then divided into shoots and roots before being oven-dried for 72 h at 65°C until their weight remained consistent. Plants' dry weights were measured and evaluated for Pb accumulation. By measuring the distance from the tip of the stem to the region above ground, the stem height was determined. Poisoning symptoms were observed during the experiment, and a ruler was used to measure the root length from the root ends to the stem base.

2.3 Determination of Pb in the plant tissue

The 0.5 g of plant samples were digested in a 2:1 ratio of HNO₃ to HClO₄ (v/v) using the open tube digestion technique (Simmons et al., 2005). A flame atomic absorption spectrophotometer (FAAS, Varian AA-220FS) was used to measure the amount of Pb present in plants. Hollow cathode lamps were run at 7.5 mA, and the wavelengths were set at 283.3 nm. Quantification was performed using a calibration curve derived from a series of diluted standard solutions, exhibiting a coefficient of determination (r²) exceeding 0.995.

2.4 Chlorophyll fluorescence and pigment measurement

At day 45, the performance index (PI), photosynthetic pigments, and chlorophyll fluorescence (Fv/Fm) of plants in all four treatments (T1-T4) were determined. These parameters were determined by the two factors: soil moisture (100% and 50% PC) and Pb addition (0 and 100 mg/kg). Chlorophyll fluorescence was measured on fully expanded leaves using a chlorophyll fluorometer (Pocket PEA, Hansatech Instruments Ltd., King's

Lynn, Norfolk, UK). Leaves were dark-adapted for 30 min using leaf clips prior to measurement. Minimal fluorescence (Fo) and maximal fluorescence (Fm) were recorded, and variable fluorescence was calculated as Fv = Fm - Fo. The maximum quantum yield of PSII was calculated as Fv/Fm = (Fm - Fo)/Fm (Maxwell and Johnson, 2000; Strasser et al., 2000; Stirbet and Govindjee, 2011). Plant samples were collected, cleansed twice with tap water, and then rinsed with distilled water to determine photosynthetic pigments. The samples were then oven-dried at 65°C for 3 days and homogenized with a mill (IKA: Japan). To measure the quantity of chlorophyll (Chl) a and Chl b, fresh leaf samples were obtained from each pot in the dark, cleaned with deionized water, and then 0.5 g of fresh leaf was chopped into tiny pieces and homogenized with 5 mL of acetone (80% v/v). The chlorophyll content was calculated according to the equations of Porra et al. (1989) and Holm (1954) based on mg chl/g fresh weight (FW) (Korkmaz et al., 2010):

$$\text{Chl a (mg/g FW)} = 12.25 \times A_{663.6} - 2.55 \times A_{646.6}$$

$$\text{Chl b (mg/g FW)} = 20.31 \times A_{646.6} - 4.91 \times A_{663.6}$$

$$\text{Chl a+b (mg/g FW)} = 17.76 \times A_{646.6} + 7.34 \times A_{663.6}$$

Where: Chl a and b are the chlorophyll a and chlorophyll b, respectively.

2.5 Data analysis

The bioaccumulation factor (BAF) was calculated according to Wilson and Pyatt (2007) as follows:

$$\text{BAF} = \frac{\text{Pb concentration in the plant}}{\text{Pb concentration in the soil}}$$

The translocation of Pb from roots to shoots was measured using the translocation factor (TF), which was calculated as follows (Cui et al., 2007):

$$\text{TF} = \frac{\text{Pb concentration in the shoot}}{\text{Pb concentration in the root}}$$

Relative growth rate (RGR) was calculated according to Hunt's equation (Hunt, 1978):

$$\text{RGR} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1}$$

Where; RGR is the relative growth rate (g/g/d), and W₁, T₁, and W₂, T₂ are the initial and final dry weights and times for each treatment, respectively.

2.6 Statistical analysis

The mean and standard error of three replicates were computed. Data were analyzed using ANOVA in SPSS (version 21.0; SPSS Inc., Chicago, IL, USA). When ANOVA indicated significant differences ($p < 0.05$), mean comparisons were performed using Dunnett's post hoc test to compare each treatment with the control ($\alpha = 0.05$). The relationships between Pb concentrations in plant tissues at $p < 0.05$ were evaluated using Pearson's correlation.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical properties of the experimental soils

As shown in Table 1, the experimental soils had a neutral pH (7.1). The cation exchange capacity (CEC) values were 31.4 cmol/kg, and the soil had a clay texture with modest amounts of organic matter (2.44 g/kg). Essential nutrient levels were comparatively high, particularly available P (40 mg/kg) and K (159 mg/kg), while total N (0.11%) was at a moderate level. These nutrients are essential for promoting the growth of roots and the absorption of metals. The soil's overall background Pb content was 10.86 mg/kg. The soil's EC value was 0.81 dS/m.

3.2 Combined effects of Pb and drought on plant growth

The plants were cultivated at a concentration of 100 mg/kg Pb, either by itself or in conjunction with

drought stress. In comparison to the control groups (T1 and T3), the drought treatments (T2 and T4) demonstrated a minor reduction in root length as the trial progressed, with a significant difference ($p < 0.05$) (Figure 1(a) and (b)). However, as compared to the control group, the stem height of plants exposed to Pb during drought circumstances showed no adverse effects. According to Table 2, there was no significant mean difference ($p > 0.05$) in the RGR and dry plant biomass data for any treatment. In the Pb-treated plants under well-watered conditions (T3; Pb + 100% PC), RGR decreased significantly with exposure time, from 0.058 ± 0.0066 at day 30 to 0.044 ± 0.0017 g/g/day at day 45 ($p < 0.05$; Table 2). The reduction in root length at the end of the trial was significantly impacted by drought stress, even though Pb had no effect ($p < 0.05$).

Table 1. Physico-chemical properties of the experimental soils

Characteristics	Value
1. Soil pH	7.1
2. Organic matter	2.44 g/kg
3. Soil texture	Clay
4. CEC	31.40 cmol/kg
5. Total nitrogen	0.11 %
6. Available phosphorus	40 mg/kg
7. Available potassium	159 mg/kg
8. Electrical conductivity	0.81 dS/m
9. Pb	10.86 mg/kg

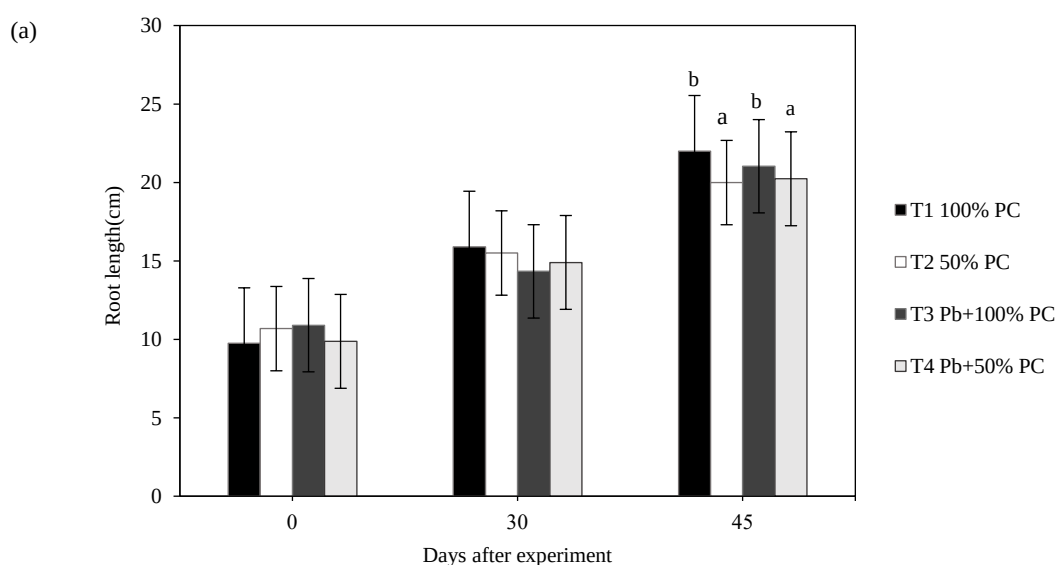


Figure 1. Root length (a) and stem height (b) of *C. esculenta* under conditions of no drought and drought, with or without Pb, at 0, 30, and 45 days. Data are mean $\pm$ SD ($n = 3$), and different letters indicate significant differences ($p < 0.05$).

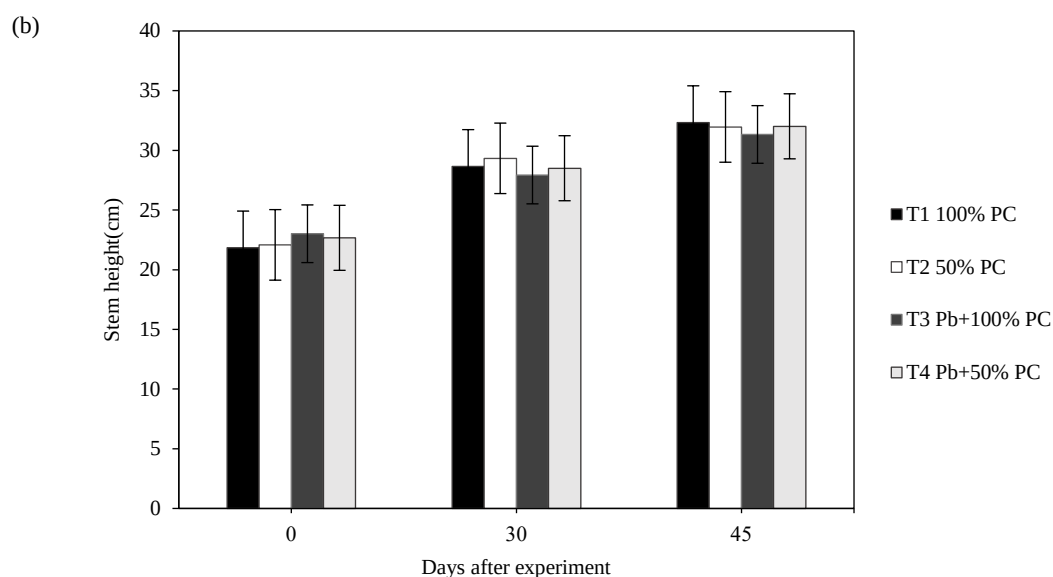


Figure 1. Root length (a) and stem height (b) of *C. esculenta* under conditions of no drought and drought, with or without Pb, at 0, 30, and 45 days. Data are mean $\pm$ SD (n=3), and different letters indicate significant differences ($p<0.05$) (cont.).

Table 2. Dry biomass production (DW, g) and relative growth rate (RGR, g/g/day) of *C. esculenta* grown in various soil treatments for 30 and 45 days

Treatments	Exposure time (days)				
	0	30		45	
	DW	DW	RGR	DW	RGR
T1: 100% PC	2.62 ^A ± 0.09	14.53 ^{a,B} ± 0.64	0.057 ^{a,A} ± 0.0076	19.53 ^{b,C} ± 2.41	0.045 ^{a,A} ± 0.0012
T2: 50% PC	3.36 ^A ± 0.11	13.48 ^{a,B} ± 0.99	0.046 ^{a,A} ± 0.0066	18.50 ^{c,C} ± 1.27	0.038 ^{a,A} ± 0.0006
T3: Pb + 100% PC	2.63 ^A ± 0.18	15.13 ^{a,B} ± 0.24	0.058 ^{a,B} ± 0.0066	19.14 ^{a,C} ± 1.49	0.044 ^{a,A} ± 0.0017
T4: Pb + 50% PC	2.84 ^A ± 0.27	16.79 ^{a,B} ± 0.68	0.059 ^{a,A} ± 0.0058	18.77 ^{a,C} ± 2.44	0.042 ^{a,A} ± 0.0002

Values are mean $\pm$ SE (n=3). Those with the same letter did not differ, while small letters indicated treatment differences and capital letters showed exposure time differences ($p<0.05$).

The drought treatment (50% PC) was selected in accordance with a mild-to-moderate water deficit that preserves plant viability and biomass for Pb uptake and phytoremediation testing based on our preliminary screening. In addition, this moisture level is relevant to field conditions, as the Thai Meteorological Department (TMD) reported that the Northern region experienced variable rainfall in 2025, including periods of below- and above-normal rainfall (TMD, 2025). The effects of Pb and drought stress on *C. esculenta* growth performance were examined throughout a 45-day pot experiment. The findings demonstrated that modest drought stress significantly reduced root length, yet plants were still able to grow under all treatments. However, neither Pb contamination nor drought stress significantly affected stem height or dry biomass. The findings show that

C. esculenta can withstand the combined stress, especially when it comes to sustaining aboveground growth in spite of limited root formation. Similar findings from earlier research have shown that while shoot development is frequently preserved under mild stress, drought stress mostly impacts root elongation due to changed water availability and osmotic adjustment (Gupta et al., 2020). The shoot tissues of *C. esculenta* can maintain growth for a longer period because of osmotic adjustment and water storage in petioles and corms. However, drought-induced inhibition of root elongation may result from limited carbohydrate allocation to belowground tissues and a decrease in root hydraulic conductivity (Vásquez et al., 2025). Similar results have been seen in other crops, such as wheat and cassava, where dryness considerably decreased root density and length, but

stem height was mostly unchanged (Bacher et al., 2022). These findings demonstrated that whereas stem height is unaffected by drought and Pb, restricted root development may indicate drought stress.

3.3 Effects of Pb and drought on chlorophyll contents and fluorescence parameters

Table 3 illustrates the chlorophyll and fluorescence of well-watered and moderate drought plants with and without 100 mg/kg Pb. After 45 days,

there was no discernible change in total chlorophyll and chlorophyll a+b ($p>0.05$), and all treatments showed chlorophyll a predominating over chlorophyll b. Likewise, no significant alterations were noted in chlorophyll fluorescence parameters (PI and Fv/Fm) between drought-treated and unstressed plants, irrespective of Pb contamination ($p>0.05$). The findings imply that fluorescence characteristics and chlorophyll contents were unaffected by Pb exposure or dryness ($p>0.05$; Table 3).

Table 3. Chlorophyll and fluorescence of *C. esculenta* growing in well-watered and severe drought conditions with and without Pb contamination after 45 days. All parameters were measured on the second fully expanded leaf beneath the growing point (values are mean $\pm$ SE; n=3)

Treatments	Chlorophyll content (mg/g FW)			PI	Fv/Fm
	Total	a	b		
T1: 100% PC	20.40 $\pm$ 1.62	12.34 $\pm$ 1.17	8.06 $\pm$ 1.04	6.42 $\pm$ 0.002	0.80 $\pm$ 0.001
T2: 50% PC	19.77 $\pm$ 0.88	12.89 $\pm$ 0.66	7.88 $\pm$ 0.94	6.38 $\pm$ 0.007	0.82 $\pm$ 0.006
T3: Pb + 100% PC	18.96 $\pm$ 1.14	11.03 $\pm$ 2.01	7.93 $\pm$ 0.15	5.97 $\pm$ 0.004	0.79 $\pm$ 0.007
T4: Pb + 50% PC	20.69 $\pm$ 1.97	12.68 $\pm$ 2.09	8.01 $\pm$ 0.88	5.98 $\pm$ 0.009	0.83 $\pm$ 0.003

C. esculenta has physiological tolerance mechanisms that protect the photosynthetic machinery from oxidative stress, according to the current study's constant fluorescence metrics (Fv/Fm and PI) and notably unchanged chlorophyll levels. Fv/Fm indicates the maximum quantum yield of PSII in dark-adapted leaves, whereas PI is an integrative index of PSII performance that is often more sensitive to stress and typically decreases under stress conditions (Baker, 2008). The maintenance of chlorophyll pigments under drought is indicative of effective osmotic adjustment and antioxidant activity, which sustain photosystem II and support continuous carbon uptake (Li et al., 2024). These findings suggest that *C. esculenta* can maintain performance under coupled Pb+drought by adjusting root development and biochemically protecting the photosynthetic apparatus.

Moreover, prior research has demonstrated that, depending on the length and intensity of the stress, drought stress can either maintain or lower chlorophyll levels (Song et al., 2026). Plant adaptability may have helped maintain high PSII efficiency under drought, as Fv/Fm values remained around 0.80 over 45 days. In healthy plants, Fv/Fm typically ranges from 0.75 to 0.85 and declines under stress (Guidi et al., 2019). The consistent Fv/Fm of *C. esculenta* may suggest effective photoprotection via antioxidant activity and non-photochemical quenching (Pluciński et al., 2023).

Interestingly, combined drought and Pb does not negatively affect PI, indicating adaptive adjustments in PSII energy fluxes that sustain photosynthesis (Li et al., 2024). Overall, steady Fv/Fm and PI show that *C. esculenta* can withstand mild drought and Pb, which is in line with findings that drought-tolerant species preserve PSII stability through improved antioxidants, osmotic adjustment, and chloroplast integrity (Ozturk et al., 2021). This pinpoints how *C. esculenta* uses biochemical compounds with antioxidant capacity to maintain the photosynthetic process to survive under stressful environments.

3.4 Pb accumulation in plant tissues

The accumulation of Pb by *C. esculenta* is presented in Table 4. When compared to control groups, Pb accumulation was noticeably higher under combined stress circumstances (T3; Pb+100% PC) ($p<0.05$). With a concentration of 513.66 mg/kg at the conclusion of the trial, plants under drought stress showed the greatest accumulation of Pb. During the first 30 days of exposure, the concentration of Pb is higher in the roots than in the shoots. After 45 days of exposure, plants in the drought-treated condition (T4) showed higher BAF levels (5.14) than those in the well-watered treatment (T3). All TF values for *C. esculenta* were less than 1.0, except for the combined stress treatment (Pb+drought) observed in a 45-day experiment. This suggests that after 45 days of

exposure, mild dryness did not affect Pb translocation, confirming its potential for phytoextraction.

According to this study, Pb translocation to shoots in *C. esculenta* was lower at 30 days than at 45 days, indicating increased root-to-shoot Pb translocation with exposure time. This pattern implies that during the early exposure period, Pb was first bound in the roots, restricting its movement to the shoots. Ahmad et al. (2011) found reduced Pb translocation in maize (*Zea mays* L.) during early stress exposure, demonstrating the plant's ability to detoxify Pb in root tissues. Similar findings were seen in a 15-day hydroponic test on Siam weed (*Chromolaena odorata*), where PEG-induced stress limited translocation to the shoots while increasing Pb absorption into the roots. This reduction in *C. esculenta* was caused by either sequestration in the root vacuoles or the precipitation of insoluble Pb salts in intercellular gaps (Yongpisanphop et al., 2017;

Srirueang et al., 2022). Pb has limited root-to-shoot translocation and is typically less mobile in plants than essential minerals, particularly during early exposure under water scarcity. By attaching to negatively charged functional groups in cell-wall pectins, restricted xylem loading, transporter control, and quick Pb retention in roots may immobilize Pb in the apoplast and decrease the mobile Pb fraction available for translocation (Rahman et al., 2024). Partial saturation of binding sites and/or alterations in root permeability and xylem loading may enhance Pb transport to shoots with prolonged exposure. According to Baker (1981), *C. esculenta* is an accumulator because $TF > 1$ after 45 days. This result implies that prolonged drought stress may raise Pb mobilization in aerial tissues, possibly as a result of drought-induced changes in xylem loading and root permeability (Rahman et al., 2024).

Table 4. Dry biomass, Pb accumulation, translocation factor (TF) and bioaccumulation factor (BAF) values of *C. esculenta* grown in contaminated soil for 0, 30 and 45 days

Treatment	Day	Dry biomass (g/plant)	Pb accumulation (mg/kg)			TF	BAF
			Shoot	Root	Total		
T3: Pb + 100% PC	0	2.63±0.18	0.00±0.00	0.00±0.00	0.00±0.00	0.00	0.00
	30	15.13±0.24	61.33±2.85 ^{a,A}	137.66±14.11 ^{a,B}	199.00±15.18 ^{a,A}	0.45	1.99
	45	19.14±1.49	168.66±11.26 ^{b,C}	277.66±1.76 ^{b,C}	446.33±12.47 ^{b,C}	0.61	4.46
T4: Pb + 50% PC	0	2.84±0.27	0.00±0.00	0.00±0.00	0.00±0.00	0.00	0.00
	30	16.79±0.68	116.33±23.85 ^{a,B}	208.33±1.45 ^{a,B}	324.66±22.73 ^{a,B}	0.56	3.25
	45	18.77±2.44	277.33±28.67 ^{b,D}	236.33±2.03 ^{b,C}	513.66±30.38 ^{b,D}	1.17	5.14

Values are mean±SE (n=3). Those with the same letter did not differ, while small letters indicated treatment differences and capital letters indicated exposure time differences at p<0.05.

Prior research has demonstrated that Pb and drought have an impact on the absorption and distribution of heavy metals in plants, including transpiration rate and water usage efficiency, which were also noted in citrus (*Citrus aurantium* L.) (Giannakoula et al., 2021). It has been demonstrated that drought stress alters the metabolism of starch in *C. esculenta* (Zhang et al., 2024), possibly having an indirect impact on metal absorption and translocation. Furthermore, it has been discovered that native *C. esculenta* wetland populations may act as bioaccumulators of Pb and other metals in contaminated soils (Chayapan et al., 2015; Davis et al., 2023). This species' capacity to transfer Pb to aboveground tissues during drought conditions points to an adaptive detoxifying mechanism that enables the safe disposal of contaminated biomass.

The overall BAF values are greater than 1 in both drought-treated and untreated plants,

demonstrating the capacity of the growing plants for Pb uptake. To combat the harmful effects of metal ions, plants often trigger antioxidative reactions (Rahman et al., 2024). According to phytochemical investigations, *C. esculenta* has a high antioxidant capacity and is known to be rich in phenolic and flavonoid compounds, which supports the idea that these metabolites aid in its tolerance mechanisms (Nugroho et al., 2025). Heavy metal toxicity often causes oxidative stress, which plants respond to by increasing peroxidase (POD)-related activities to maintain cellular integrity and photosynthetic activity (Rahman et al., 2024). Some Araceae species, such as elephant foot yam (*Amorphophallus paeoniifolius*), have been reported to accumulate heavy metals through similar enzyme-mediated detoxification responses, which implies that metal tolerance and sequestration characteristics may be present within this family (Singh et al., 2017). Therefore, the Pb

tolerance and accumulation observed in *C. esculenta* in the present study reflect similar family-level traits.

Studies showing that BAF and TF can demonstrate their phytoremediation potential for Pb-contaminated soils are supported by the Pb accumulation in *C. esculenta* throughout the course of the 45-day treatment. Our results indicate that drought-induced increases in Pb mobility and plant adaptation mechanisms enhance phytoextraction efficacy (Acharya et al., 2025). *C. esculenta* is therefore a viable option for phytoremediation techniques in regions with fluctuating water levels because of its Pb tolerance, drought adaptability, and translocation capabilities. Wetland plants that are not intended to be hyperaccumulators are examples of wild native or indigenous species that often adapt to the natural habitat and may have unexplored potential to clean up the environment. Hence, Chayapan et al. (2015) suggest *C. esculenta* for heavy metal-contaminated soil/sediments. Growing *C. esculenta* in Pb-contaminated soils could jeopardize food safety, even though it can absorb and translocate Pb. Clearly separating remediation plots from areas used for food production, harvesting at the best times to maximize metal removal, handling contaminated biomass safely and regulating its disposal or treatment, and managing risks to avoid livestock grazing and unintentional exposure are all important aspects of practical phytoremediation applications. Water-saving management can enhance phytoremediation and contain pollutants in drought-prone locations.

4. CONCLUSION

This experiment demonstrated that *C. esculenta* can withstand 45 days of combined drought and Pb stress while maintaining growth, photosynthetic efficiency, and chlorophyll integrity. Even though Pb's mobility was restricted after its initial exposure at 30 days, the quick translocation of Pb to aerial tissues during a protracted mild drought gives evidence of accumulator properties. The results of the study demonstrate the promising capacity of *C. esculenta* as a phytoextraction agent for Pb in dry polluted soils. These results shed important light on *C. esculenta*'s potential for phytoremediation, especially in drought-prone areas.

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AUTHOR CONTRIBUTIONS

Jampasri K. conceptualized the study, developed the methodology, supervised the research, managed project administration, acquired funding, and performed a writing-review and editing. Saeng-ngam S. conceptualized the study, developed the methodology, and performed writing—original draft preparation and writing—review and editing. Larpkern P. developed the methodology, conducted the investigation, curated the data, and performed formal analysis, and prepared figures and visualizations. Moungrimuangdee B. developed the methodology, conducted the investigation, curated the data, performed formal analysis, and performed a writing review and editing.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Heavy Metal Content in Pavement Mushrooms Harvested within the Urban Area of Sarajevo (Bosnia and Herzegovina) and an Assessment of Associated Health Risks

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ABSTRACT

This study investigated the ability of pavement mushrooms (*Agaricus bitorquis* (Quél.) Sacc.) to uptake heavy metals (Cu, Zn, Pb, Cr, Cd, and Ni) from the soil in Sarajevo's urban area and the potential health hazards related to their consumption. The levels of tested heavy metals in soil and mushroom samples were determined using the flame atomic absorption spectroscopy technique. The phytoextraction potential was estimated using bioaccumulation factor (BAF) analysis, while the evaluation of the non-carcinogenic, long-term risk to human health through the consumption of the studied mushrooms was performed using the Target Hazard Quotient (THQ) value. The study revealed that particular soils within the urban zone of Sarajevo are contaminated with Cu and Pb. The average content of tested heavy metals in the fruiting bodies of pavement mushrooms decreased in the order of Cu > Zn > Pb > Cr > Ni > Cd, regardless of the soils from which the mushrooms were collected. The BAF values obtained in this study indicated that pavement mushrooms have a high ability to accumulate Cd and Cu, while showing a limited ability to absorb Pb and Ni. The THQ values for all heavy metals analysed in pavement mushrooms were considerably lower than one for both adults and children, suggesting that consuming pavement mushrooms gathered from experimental sites poses no non-carcinogenic health risks related to the heavy metals studied.

HIGHLIGHTS

- Particular soils within the urban zone of Sarajevo are contaminated with Cu and Pb.
- The pavement mushrooms have a high ability to accumulate Cd and Cu.
- This report offers valuable insights into the potential health risks of consuming pavement mushrooms.

1. INTRODUCTION

Rapid urbanization, coupled with intensive industrialization and fast population growth, generates considerable quantities of pollutants, including toxic heavy metals, that adversely affect air and soil quality, particularly in urban areas (Tu et al., 2025). Toxic heavy metals, including cadmium (Cd), chromium (Cr), and lead (Pb), are recognized for their serious health implications for humans, stemming from their bioaccumulation and persistent nature in the environment. Sustained exposure to these pollutants has been correlated with the initiation of multiple

cancers, including those that affect the skin, lungs, and kidneys (Balali-Mood et al., 2021). Essential heavy metals vital for human existence, including zinc (Zn) and copper (Cu), can also be harmful and carcinogenic when ingested in excessive quantities (Khatoon et al., 2025). Consequently, the rising levels of heavy metals in the environment have emerged as a significant global environmental issue (Kholikulov et al., 2025).

The first step in resolving this issue is to monitor both the presence and the amounts of heavy metals in the environment. Up to now, investigations into the concentrations of heavy metals in the

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environment have shown that numerous mushroom species have a high ability to accumulate heavy metals (Ab Rhaman et al., 2021; Qin et al., 2024; Liu et al., 2025). Generally, fungal mycelium can accumulate heavy metals in concentrations significantly higher than the substrate on which it develops and lives. In the research conducted by Zhu et al. (2011), the ranges of Zn, Cd, Cr, and Pb in 14 different wild-growing edible mushrooms collected from Yunnan Province in China were 42.9-94.3, 0.06-0.58, 10.7-42.7, and 0.67-12.9 mg/kg, respectively. High concentrations of heavy metals in edible wild mushrooms were also observed in the study by Singh and Nyau (2020), ranging from 1.1 to 2.0 mg/kg for Pb, 46.9 to 141.8 mg/kg for Cu, 0.1 to 6.6 mg/kg for Cd, and 44.8 to 79.7 mg/kg for Co. This study found that the levels of heavy metals in a greater number of the mushrooms examined were above the threshold limits established by the World Health Organization (WHO, 2021). It follows from the above that there is a potential risk associated with the consumption of edible wild mushrooms that residents gather from natural or urban areas and use as food ingredients (Shackleton et al., 2017).

Dowlati et al. (2021) reported that the ability of mushrooms to accumulate heavy metals from the soil is influenced by numerous factors, including the genetic characteristics of fungi, their growth stages, and various edaphic factors such as total and available heavy metal content, soil pH, organic matter, and clay content. Additionally, most mushrooms respond to exposure to heavy metals by synthesizing metallothionein-like proteins, which are essential for binding heavy metals, thereby promoting their accumulation in fruiting bodies (Aslam et al., 2025).

Agaricus bitorquis (Quél.) Sacc., commonly known as banded agaric, urban agaricus, or pavement mushroom, is a species of fungi that can be found in fields, meadows, and along the edges of pavements, and sometimes even erupts through asphalt. This mushroom is tasty, featuring a slightly dry and pungent scent (Zhao et al., 2023). In the Sarajevo region, it typically fruits from June to September, often in association with coniferous and deciduous trees. Its distribution in the Sarajevo urban area is relatively extensive, with occurrences noted at several sites, primarily in urban parks and promenades.

It is widely recognized that pavement mushrooms are abundant in nutrients and health-promoting components (Muszyńska et al., 2017; Usman et al., 2021). It is also a well-established fact

that they can accumulate heavy metals from polluted soils, but to date, this type of research has not been carried out in Bosnia and Herzegovina. This study aimed to assess the ability of pavement mushrooms to absorb certain heavy metals from the soil in Sarajevo's urban area and to evaluate the potential health risks for humans from consuming these mushrooms. This study is pioneering in evaluating the accumulation of heavy metals in the fruiting bodies of pavement mushrooms that grow in Bosnia and Herzegovina. In this light, this study provides valuable information for both authorities and citizens about the risk of consuming pavement mushrooms grown in the Sarajevo urban area.

2. METHODOLOGY

2.1 Materials

Pavement mushroom (*A. bitorquis*) is an edible white mushroom belonging to the *Agaricus* genus. It is distinguished by its “double-skirted” stem and its propensity to thrive in urban settings. Characterized by its stout and firm structure, this mushroom has a dry, smooth, greyish brown to off-white cap that varies from convex to flat, typically measuring 4 to 18 cm in diameter. The stipe ranges from 3 to 11 cm long and 1 to 4 cm thick. Notably, it possesses a robust upper ring that resembles a funnel, along with a more delicate, skirt-like lower ring. Initially, the gills exhibit a dark pink to clay colour and become chocolate brown upon reaching maturity. The spore print is dark brown (Lu et al., 2020; Yingying et al., 2023).

2.2 Chemicals

All used reagents were of analytical grade. HNO₃ (69%), HCl (37%), and H₂SO₄ (95%) were purchased from Merck (Darmstadt, Germany), whereas a 1 M KCl solution was obtained from Semikem, Sarajevo. Heavy metal stock solutions were prepared through the dilution of the respective 1,000 mg/L standards (Merck, Germany). Working solutions were prepared daily by suitable dilution using distilled water.

2.3 Experimental sites

The soil samples and fruiting bodies of the wild edible mushroom *A. bitorquis* were collected at weekly intervals from May to the end of June 2025 from four distinct sites within the urban area of Sarajevo (Figure 1).

The sites were as follows: (1) central part of Wilson's Promenade (43.853971° N, 18.400323° E),

(2) urban garden nestled in the heart of Franjo Rački Street at number 3 (43.853766° N, 18.403904° E), (3) meadow located near the western side of Wilson's Promenade (43.851689° N, 18.387352° E), and (4) walkway next to the M18 route (43.852857° N,

18.387405° E). All selected sites represented areas with a higher prevalence of these mushrooms, which is why they were chosen. In total, twelve *A. bitorquis* mushrooms were collected from site 1, eight from sites 2 and 3, and nine from site 4.



Figure 1. Experimental sites from which soil and mushroom samples were collected

2.4 Soil chemical analysis

At each site under investigation, soil samples weighing about 0.5 kg were taken just below the mushroom fruiting bodies at a depth of 10 to 30 cm. Soil pH was measured in 1 M KCl solution utilizing a pH meter at a ratio of 1:2.5 (ISO 10390, 2021). Organic matter content and the available forms of phosphorus and potassium were evaluated through the potassium dichromate redox method (ISO 14235, 1998) and the ammonium lactate (AL) method (Egnér et al., 1960), respectively.

Extraction of heavy metals from soil samples was performed using acid digestion. Briefly, 3 g of air-dried, 1-mm sieved soil sample was placed in a crucible and ignited in a muffle furnace at 550°C for 6 h. The resulting ash was treated with 20 mL of aqua regia (a mixture of HCl and HNO₃ in a ratio of 3:1),

followed by heating on a hot plate for 1 h at 60°C. After the mixture cooled to room temperature, 10 mL of deionized water was added, followed by filtration through quantitative filter paper (Whatman, No. 42) into a 100 mL volumetric flask. The final volume was then brought to 100 mL with deionized water (ISO 11466, 1995).

2.5 Extraction of heavy metals from mushroom samples

Immediately following the harvest, all mushroom samples were transported in a portable refrigerator at a temperature of 10°C to the Laboratory of the Faculty of Agriculture and Food Sciences in Sarajevo, where they were stored at 4°C until further analysis. Before commencing the heavy metal extraction, mushroom samples were dried as follows:

fresh and cleaned mushroom samples (each weighing approximately 100 g) were dried in an oven at 40°C for three days and then ground into powder with an electric blender. The resulting powdered material was separately stored in resealable plastic bags.

Mushroom samples were digested according to the method described by [Lisjak et al. \(2009\)](#). Briefly, 2 g of dry mushroom powder samples were weighed and transferred to a crucible, and then ignited in a muffle furnace at 550°C for 6 h. Upon reaching room temperature, the resulting ash was treated with 10 mL of a mixture of HNO₃ and H₂SO₄ in a ratio of 2.5:1, followed by heating on a hot plate for 20 min at 60°C. After 30 min, 10 mL of deionized water was added; then the mixture was filtered through quantitative filter paper (Whatman, No. 42) into a 50 mL volumetric flask. The final volume was adjusted to the mark with deionized water. Heavy metal extraction was performed on the three mushroom samples from each experimental site.

2.6 Determination of heavy metals in soil and mushroom samples

Concentrations of the analysed heavy metals (Cu, Zn, Mn, Pb, Cr, Cd, Ni, Co) in soil and mushroom samples were measured according to the ISO 11047 method, utilizing atomic absorption spectrophotometry ([ISO 11047, 1998](#)) with a Shimadzu Model AA-7000 instrument (Shimadzu Instruments, Tokyo, Japan). Heavy metal concentrations in both soil and mushroom samples were expressed in mg/kg of dry weight.

2.7 Bioaccumulation factor (BAF)

Bioaccumulation factor (BAF) indicates the degree of metal bioaccumulation in plants/mushrooms compared to their concentration in the soil and is calculated using Equation 1 ([Ladislav et al., 2012](#)):

$$BAF = \frac{C_{\text{mushroom}}}{C_{\text{soil}}} \quad (1)$$

Where; C_{mushroom} represents the metal content in mushrooms (mg/kg) and C_{soil} represents the metal content in soil or other growth media.

2.8 Health risk analysis

The health risks of heavy metals due to consuming pavement mushrooms were evaluated using the target hazard quotient (THQ). According to the United States Environmental Protection Agency ([USEPA, 2011](#)), THQ is defined as the ratio of the

estimated daily intake (EDI) of a metal to its oral Reference Dose (RfD), and it was calculated using Equation 2 ([Nowakowski et al., 2021](#)):

$$THQ = \frac{\text{Estimated daily intake of metal (EDI)}}{RfD} \quad (2)$$

Where; RfD represents the oral reference dose for each specific contaminant, i.e., the highest level of contaminant at which no adverse health effects are expected. The RfD values established by the [USEPA \(2011\)](#) are as follows: 0.001 mg/kg/day for Cd, 0.003 mg/kg/day for Cr, 0.040 mg/kg/day for Cu, 0.020 mg/kg/day for Ni, 0.035 mg/kg/day for Pb, and 0.3 mg/kg/day for Zn. Any THQ value greater than 1 indicates a high health risk due to the consumption of contaminated food.

EDI quantifies the transfer of contaminants from plants or mushrooms to the human body, as calculated by Equation 3 ([Chukwuka et al., 2023](#)):

$$EDI = \frac{C \times IR}{\text{body weight}} \quad (3)$$

Where; C represents the heavy metal content in the analysed mushroom sample (mg/kg of dry weight); IR represents the daily ingestion rate of mushrooms per capita (0.0066 kg/person/daily), and BW represents body weight (for adults 70 kg, for children 24 kg) ([Senila et al., 2024](#)).

2.9 Statistical analysis

All the measurements were performed in triplicate on each mushroom sample and the results were expressed as mean±standard deviation. Data were analysed using one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) tests at the 5% level ($p \leq 0.05$) to compare treatment means.

3. RESULTS AND DISCUSSION

In this study pavement mushrooms were collected from four distinct sites within the urban area of Sarajevo. Regardless of location, the studied soils were slightly alkaline, contained a very high level of organic matter, and were sufficiently supplied with available phosphorus and potassium ([Table 1](#)). Soils rich in organic matter and adequately supplied with nutrients are exceptionally favourable for mushroom growth, which may be one of the key reasons for the high prevalence of pavement mushrooms in the studied area. However, the chemical properties of

these soils are not typical for soils outside the urban area of Sarajevo, suggesting that the formation of soils at the experimental sites is the result of the intensive influence of anthropogenic factors. [Asabere et al. \(2018\)](#) indicated that urbanization factors, including

urban soil management, housing, traffic, construction, and waste, distinguish urban soils from those found in natural, semi-natural, and agricultural regions. These findings are in line with the findings of [Sager \(2020\)](#), [Zandybay et al. \(2024\)](#), and [Sun et al. \(2025\)](#).

Table 1. Chemical characteristics of the soil at the experimental sites

Parameter	Experimental site*			
	1	2	3	4
pH KCl	7.32	7.41	7.31	7.47
Organic matter (%)	9.44	6.21	6.81	15.79
Available P (mg/100 g)	24.83	21.66	30.11	22.11
Available K (mg/100 g)	35.33	30.11	38.45	31.03

* Experimental site: (1) central part of Wilson's Promenade; (2) urban garden nestled in Franjo Rački Street; (3) meadow located near the western side of Wilson's Promenade; (4) walkway next to the M18 route

In the current research, the soil at experimental sites 3 (west side of Wilson's Promenade) and 4 (walkway next to the M18 route) showed notably higher concentrations of Pb and Cu ([Table 2](#)), which can also be linked to anthropogenic influences, as these soils are located near roadways. [Hawari et al. \(2021\)](#) reported that most of the Cu and Pb found in soils near roadways are a result of emissions from vehicles. Similar observations were noted in the

studies conducted by [Lee et al. \(2021\)](#) and [Kholikulov et al. \(2024\)](#).

The mean levels of all other heavy metals studied, namely Zn, Cr, Cd, and Ni, in the soil samples analysed were beneath the threshold limits set by the legislation in Bosnia and Herzegovina ([Official Gazette of FBiH, 2022](#)). In accordance with this legislation, the maximum permissible levels for Cu, Zn, Pb, Cr, Cd and Ni in soils are set at 80, 200, 100, 100, 1, and 75 mg/kg, respectively.

Table 2. Heavy metal levels in soil samples collected from the experimental sites

Experimental site*	Heavy metals content (mg/kg dry weight)					
	Cu	Zn	Pb	Cr	Cd	Ni
1	35.1±1.6 ^c	51.3±7.3	74.8±6.2 ^c	7.6±0.9	0.16±0.02	24.9±3.2 ^b
2	36.0±1.4 ^c	58.8±4.9	82.3±6.5 ^c	9.7±1.3	0.16±0.02	26.9±3.1 ^b
3	49.2±3.4 ^b	56.7±3.3	143.1±17.6 ^b	8.2±0.9	0.14±0.02	34.9±3.1 ^a
4	83.6±4.6 ^a	59.9±4.6	218.1±12.9 ^a	9.4±0.7	0.15±0.03	39.5±3.7 ^a
F test	s.	n.s.	s.	n.s.	n.s.	s.
LSD _{0.05}	5.69	-	22.26	-	-	6.11

* Experimental site: (1) central part of Wilson's Promenade; (2) urban garden nestled in Franjo Rački Street; (3) meadow located near the western side of Wilson's Promenade; (4) walkway next to the M18 route; Different letters in the same column indicate statistically significant differences ($p \leq 0.05$); s-significant; n.s.-non significant

This study found no significant differences in the levels of Zn, Cr, and Cd among the tested soils. Conversely, a significant variation in the levels of Ni was observed among the soil samples that were analysed. In this context, the average concentrations of Ni from sites 3 (meadow located near the western side of Wilson's Promenade) and 4 (walkway next to the M18 route) were significantly higher than those from sites 1 (central part of Wilson's Promenade) and 2 (urban garden nestled in Franjo Rački Street). Increased concentrations of Ni in soils near roadways (sites 3 and 4) may arise from the abrasion of tires and

brake pads, as well as from gasoline residues. These observations correspond with the findings of [Radziemska and Fronczyk \(2015\)](#).

Numerous studies have revealed that mushrooms can accumulate certain heavy metals at much higher concentrations than the substrate on which they grow and thrive, indicating that mushrooms are equipped with a highly efficient mechanism that allows them to absorb certain heavy metals from the soil efficiently ([Širić and Humar, 2023](#); [Bucurica et al., 2024](#); [Stihi and Dumitrescu, 2025](#)). In this context, it is widely accepted that

mushrooms generally absorb a higher content of heavy metals compared to plants that grow in the same area (Liu et al., 2022).

The average values of Cu, Zn, Pb, Cr, Cd, and Ni in the fruiting bodies of pavement mushrooms collected from four different experimental sites are presented in Table 3.

The average content value of tested heavy metals in the fruiting bodies of pavement mushrooms decreased in the order of Cu > Zn > Pb > Cr > Ni > Cd, regardless of the experimental sites from which pavement mushrooms were collected. The levels of Cu and Pb exceed the recommended limits of 30 mg/kg for Cu and 0.3 mg/kg for Pb in food as set by the World

Health Organization (WHO, 2021). The presence of significant amounts of Cu and Pb in the tested pavement mushrooms is not unexpected, considering that some of the soils from which these mushrooms were collected are contaminated with these elements. The study conducted by Demirbas (2000) revealed that the pavement mushrooms exhibited lower concentrations of Cu and Pb in their fruiting bodies, with mean values of 26.4 mg/kg for Cu and 1.34 mg/kg for Pb, respectively. These results were also anticipated since the soil where these mushrooms grew had a lower content of Cu and Pb compared to the soil in the current study.

Table 3. Heavy metal levels (mg/kg, dry weight basis) in pavement mushroom samples collected from the experimental sites

Experimental site*	Heavy metals content					
	Cu	Zn	Pb	Cr	Cd	Ni
1	63.5±5.4 ^b	41.6±5.9 ^c	2.2±0.3 ^c	1.7±0.2	0.63±0.07 ^b	1.6±0.3 ^b
2	81.1±6.2 ^a	71.2±5.4 ^a	3.8±0.3 ^b	1.7±0.3	0.56±0.12 ^b	1.6±0.4 ^a
3	63.6±7.0 ^b	54.4±6.1 ^b	5.5±0.5 ^a	1.7±0.2	0.83±0.08 ^a	0.7±0.3 ^c
4	74.3±5.8 ^a	52.6±2.4 ^b	4.4±0.6 ^b	1.8±0.3	0.49±0.08 ^b	1.3±0.2 ^b
F test	s.	s.	s.	n.s.	s.	s.
LSD _{0.05}	9.61	9.82	0.81	-	0.16	0.48

* Experimental site: (1) central part of Wilson's Promenade; (2) urban garden nestled in Franjo Rački Street; (3) meadow located near the western side of Wilson's Promenade; (4) walkway next to the M18 route; Different letters in the same column indicate statistically significant differences ($p \leq 0.05$); s-significant; n.s.-non significant

According to the data for a number of *Agaricus* species (Kosanić et al., 2017; Rashid et al., 2018), the concentrations of Ni and Cr are mostly below 2 mg/kg. This is in agreement with the present results. In contrast, the study by Širić et al. (2016) found higher mean values for Ni (3.62 mg/kg) and Cr (3.01 mg/kg) in the mushroom *Agaricus campestris*, indicating that the accumulation of Ni and Cr is species-specific. The study revealed a significant difference in the concentrations of Cu, Zn, Pb, Cd, and Ni in pavement mushrooms collected from four different experimental sites. The fruiting bodies of pavement mushrooms collected from experimental site 2 (an urban garden nestled in Franjo Rački Street) exhibited a significantly higher content of Zn and Ni compared to those gathered from other experimental sites. Conversely, the highest Pb content was observed in the fruiting bodies of the pavement mushrooms gathered from experimental sites 3 (a meadow located near the western side of Wilson's Promenade) and 4 (a walkway next to the M18 route). It was an expected outcome, taking into account that the soils at experimental sites 3 and 4 possess the highest content of Pb. There was no significant difference in Cr

content in pavement mushrooms among the experimental sites.

Bioaccumulation factor (BAF) is an important index for evaluating the ability of plants or mushrooms to transfer heavy metals from soil into their harvestable (edible) parts. A BAF value higher than 1 indicates that the mushroom has a strong capacity to accumulate the studied metal (Zakaria et al., 2021). Table 4 displays the BAF values for the heavy metals that were analysed.

In the current study, the highest BAF value was observed for Cd, while the least was noted for Pb and Ni. Various studies have demonstrated that mushrooms generally possess a significant ability to absorb and accumulate Cd in their fruiting bodies, indicating that Cd is one of the primary sources of health risks associated with edible mushrooms (Gałowska and Pietrzak-Fiećko, 2021; Ordak et al., 2025). However, the high BAF values of pavement mushrooms for Cd observed in this study should be interpreted cautiously due to the fact that the determined Cd content in all examined soils was relatively low.

Table 4. Bioaccumulation factor (BAF) of selected heavy metals in pavement mushrooms obtained from different sites

Experimental site*	Bioaccumulation factor					
	Cu	Zn	Pb	Cr	Cd	Ni
1	1.81	0.81	0.03	0.22	3.94	0.06
2	2.25	1.21	0.05	0.18	3.50	0.06
3	1.29	0.96	0.04	0.21	5.93	0.02
4	0.95	0.88	0.02	0.19	3.27	0.03

* Experimental site: (1) central part of Wilson's Promenade; (2) urban garden nestled in Franjo Rački Street; (3) meadow located near the western side of Wilson's Promenade; (4) walkway next to the M18 route

From a health point of view, low BAF values for Pb in pavement mushrooms are highly desirable since Pb is a well-established hazardous heavy metal that can cause a number of health hazards in humans (Jomova et al., 2025). In different studies, it was noted that the BAF values for Pb in mushrooms are below 1, suggesting that mushrooms typically possess a limited capacity to absorb Pb from the soil (Falandysz and Borovička, 2013; Mleczek et al., 2025). On the other hand, Hacıoğlu et al. (2025) reported BAF values for Pb exceeding 1 in specific mushroom species in their study. These variations indicate that the mushrooms' ability to uptake Pb and generally heavy metals can vary widely depending on the mushroom species, heavy metal content in the soil and the soil's physical and chemical properties (Gebrelibanos et al., 2016). Among these soil properties, soil pH is considered the most important factor controlling the solubility and mobility of heavy metals. In alkaline conditions (high pH), most heavy metals, including Pb, tend to form insoluble precipitates like hydroxides, carbonates, or phosphates, thereby decreasing their bioavailability (Adamczyk-Szabela and Wolf, 2022). In this research, all the analysed soils where pavement mushrooms thrived showed an alkaline reaction, likely resulting in

reduced Pb absorption by the pavement mushrooms.

The BAF values for Cu and Zn in pavement mushrooms were observed to be in the ranges of 0.95-2.25 and 0.81-1.21, respectively, demonstrating that these mushrooms can efficiently transfer Cu and Zn from the soil to their fruiting bodies. High BAF values for Cu and Zn in various mushroom species were similarly reported in the studies of Budzyńska et al. (2022) and Wang et al. (2024). Many scientists argue that mushrooms do not possess effective mechanisms to restrict the transfer of Cu and Zn from the growth medium into their bodies, as these elements play a crucial role in numerous metabolic pathways and physiological functions in mushrooms (Wang et al., 2015; Golubkina et al., 2025). The outcomes of this study are in line with this hypothesis.

Nonetheless, it is significant to point out that at high concentrations, Zn and Cu might negatively influence mushroom growth and development. Many mushroom species exhibited abnormal morphological changes when subjected to environments rich in Zn and Cu (Golubeva et al., 2020; Robinson et al., 2021).

The established THQ values for each heavy metal found in pavement mushrooms are summarized in Table 5.

Table 5. THQ values for heavy metals in pavement mushrooms collected from different sites

Experimental site*	Target hazard quotient											
	Cu		Zn		Pb		Cr		Cd		Ni	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child
1	0.149	0.437	0.013	0.035	0.006	0.017	0.053	0.156	0.059	0.173	0.008	0.022
2	0.191	0.558	0.022	0.065	0.010	0.029	0.053	0.156	0.053	0.154	0.008	0.022
3	0.150	0.558	0.017	0.049	0.015	0.043	0.053	0.156	0.078	0.223	0.003	0.010
4	0.175	0.511	0.017	0.048	0.012	0.034	0.057	0.165	0.046	0.135	0.006	0.018

* Experimental site: (1) central part of Wilson's Promenade; (2) urban garden nestled in Franjo Rački Street; (3) meadow located near the western side of Wilson's Promenade; (4) walkway next to the M18 route

The THQ values for all heavy metals tested in pavement mushrooms were much lower than 1 for both adults and children, suggesting that the consumption of pavement mushrooms collected from

experimental sites has no non-carcinogenic, long-term risk to human health in terms of contamination with the heavy metals examined. To better assess health risks, the THQ of a range of heavy metals can be

further summed to calculate the hazard index (HI), which reflects the combined health risk associated with exposure to several heavy metals. If the HI exceeds 1, it means the health risk is elevated. From the results shown for THQ for each heavy metal analysed, it is evident that the HI values would not reach the critical threshold that suggests a greater health risk for those consuming the mushrooms studied. However, this observation requires careful consideration, as the amounts of certain heavy metals assessed, specifically Cu and Pb, were above the acceptable thresholds set by the WHO. In this context, it is essential to acknowledge that the continuous intake of pavement mushrooms gathered from Sarajevo's city area may potentially result in a serious health hazard.

4. CONCLUSION

This study's findings reveal that particular soils within the urban zone of Sarajevo are contaminated with Cu and Pb. The mean concentrations of heavy metals in the fruiting bodies of pavement mushrooms collected from soil at the experimental sites in Sarajevo's urban area were observed to decrease in the following order: Cu > Zn > Pb > Cr > Ni > Cd. The BAF values obtained for the heavy metals tested indicated that pavement mushrooms have a strong capacity to accumulate Cd and Cu, while showing a limited ability to absorb Pb and Ni from the soil at the experimental sites. The observed BAF values for Cd and Cu ranged from 3.27 to 5.93 and from 0.95 to 2.25, respectively. In contrast, the ranges for Pb and Ni were 0.02 to 0.05 and 0.02 to 0.06, respectively. The THQ values for all heavy metals analysed in pavement mushrooms were significantly below 1 for both adults and children, suggesting that the consumption of pavement mushrooms collected from experimental sites has no significant non-carcinogenic risks to human health in relation to the heavy metals studied. While calculated THQ values suggest negligible non-carcinogenic risk at typical consumption rates, the exceedance of food safety limits for Cu and Pb indicates that frequent or long-term consumption could still pose potential health concerns.

AUTHOR CONTRIBUTIONS

Conceptualization, A.H. and S.M.; Methodology, A.H.; Software, A.T.; Validation, J.A., A.H. and D.P.; Formal Analysis, J.A. and S.M.; Investigation, S.M. and A.H.; Resources, J.A.; Data Curation, S.M.; Writing-Original Draft Preparation, S.M.; Writing-Review and

Editing, A.H., D.P., A.T., and J.A.; Supervision, S.M.; Project Administration, S.M.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Integrating Design Thinking into Household Organic Waste Management: A Participatory Approach Toward a Circular Economy in Cirebon City, Indonesia

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ABSTRACT

Household organic waste management in many Indonesian cities remains dominated by linear collect-transport-dispose systems, limiting the implementation of circular economy principles. In Cirebon City, low community participation and limited source separation remain key challenges. This study aims to integrate the Design Thinking framework into the assessment of household organic waste management behavior to support the transition toward a circular economy. A mixed-methods approach was applied, combining a quantitative survey of 300 households and participatory qualitative observations involving 30 respondents from three active community-based waste banks. Five behavioral indicators awareness and understanding, attitudes toward the program, actual waste management practices, willingness to participate, and perceptions of circular economy benefits were measured using a Likert scale questionnaire. Data were analyzed using descriptive statistics and Spearman's rank correlation analysis. The results show a significant positive relationship between awareness, willingness to participate, and perceived benefits of the circular economy ($p=0.395$; $p<0.01$). Field implementation of the Design Thinking stages (Empathize Test) resulted in a 23% increase in community participation, improved perception of economic benefits, and the formation of habitual organic waste sorting behavior. Prototype trials using three types of dry materials (sawdust, charred rice husk, and raw rice husk) indicated that sawdust was the most effective, maintaining composting temperature stability (38-42°C) and producing mature, odor-free compost. This study contributes a participatory behavioral assessment framework that integrates Design Thinking into household organic waste management. The findings provide practical implications for local governments and community-based programs in strengthening circular economy implementation at the household level.

HIGHLIGHTS

- Household organic waste dominates the waste composition in Cirebon
- Design Thinking is applied as a behavioral assessment and participatory framework
- The layered composting system effectively reduces odor, leachate, and maggots
- Community participation increased by 23% after prototype iteration
- Participatory innovation supports the transition toward a circular economy

1. INTRODUCTION

Organic waste is a dominant component of household waste in Indonesia, accounting for more than 40% of the total national waste generation

(SIPSN, 2024). The lack of optimal handling of organic waste at the source, namely households, has the potential to produce methane (CH₄) emissions through anaerobic decomposition in waste piles.

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Studies in several locations in Indonesia confirm that landfills are a major source of methane emissions, which is a potent greenhouse gas contributing to climate change and other risks such as landfill fires due to methane gas accumulation (Citrasari et al., 2025; Kristanto and Koven, 2019; Permatasari et al., 2025).

The Circular Economy (CE) approach offers sustainable solutions through resource recovery and waste reduction at source. However, most studies in Indonesia still focus on technical and infrastructure aspects, while the social dimensions and community behavior as the main drivers of the circular system remain under explored (Gunamantha et al., 2023). In particular, existing studies on organic waste management in Indonesia predominantly emphasize technical and infrastructure-based solutions, with limited attention to household-level behavioral assessment and participatory design approaches that integrate circular economy principles. This study addresses this gap by integrating Design Thinking as both a behavioral assessment tool and a participatory intervention framework at the household level. Although various organic waste treatment technologies have been developed, their effectiveness is often limited due to cost factors, space requirements, and a lack of user skills (Kharola et al., 2022; Manea et al., 2024; Wicaksana et al., 2025).

Furthermore, although public awareness of environmental issues is relatively high, waste sorting practices at the household level remain low. This gap between knowledge and behavior indicates the need for a human-centered approach to bridge the gap between awareness and concrete action. Design Thinking (DT) is relevant because it is oriented towards empathy, collaboration, and solution iteration through the stages of empathize, define, ideate, prototype, and test (Buhl et al., 2019).

Therefore, this study emphasizes the importance of shifting from a linear waste management system to a circular economy model that places the community as part of the resource management cycle. The integration of the DT method is used to identify behavioral barriers and design participatory solutions that are contextualized to the social and institutional characteristics of Cirebon City. This study positions DT not only as a solution design method but also as a behavioral assessment tool to understand the needs, barriers, and motivations of the community in managing household organic waste.

By integrating a survey of 300 respondents and a collaborative participatory process with 30 households in three Waste Bank Communities in Cirebon City, this approach provides empirical understanding of the interaction between awareness, attitudes, practices, participation, and perceptions of economic benefits in the context of a circular economy. This participatory approach bridges the social and technical aspects of environmental management through simple and contextual solution designs, such as a layer composting system based on local materials (sawdust, charred rice husk, and raw rice husks). This system is easy to apply, does not require special skills, and is low-cost. Empirical studies show that decentralized composting led by civil society can provide environmental and social benefits in large cities (Amato et al., 2024).

Based on this background, this study aims to assess the level of understanding, attitudes, practices, and readiness of households to participate in organic waste management; identify behavioral barriers and opportunities for circular economy implementation in the local context; and develop design-driven policy and intervention recommendations through a participatory Design Thinking approach. Importantly, the novelty of this study lies in the integration of Design Thinking as both a behavioral assessment tool and a participatory intervention framework in household organic waste management. Unlike previous studies that primarily focus on technical or infrastructure based solutions, this research emphasizes household level behavioral dynamics, co-design processes, and prototype testing to support circular economy implementation.

The study contributes a participatory assessment framework that links awareness, attitudes, practices, and willingness to participate with design-driven interventions. These findings provide practical implications for local governments and community-based waste management programs by demonstrating how simple, low-cost, and user-centered composting solutions can enhance community participation and support the transition toward a circular economy at the household level.

2. METHODOLOGY

2.1 Study location

This study was conducted in Cirebon City, West Java Province, Indonesia. Cirebon City was selected as the study area due to its persistent challenges in

municipal solid waste management. The city still relies on an open dumping system at the final disposal site, and several waste-related incidents, including landfill fires, have occurred in recent years. These conditions indicate limited waste reduction at source and low household level participation in waste sorting, making Cirebon City a relevant case for examining household organic waste management behavior and participatory interventions towards a circular economy.

Administratively, Cirebon City is divided into five subdistricts: Harjamukti, Lemahwungkuk, Pekalipan, Kejaksan, and Kesambi, which represent diverse socio-economic and environmental characteristics. These differences formed the basis for

selecting proportional survey locations and three active community-based Waste Banks as sites for participatory Design Thinking activities (Figure 1).

Topographically, Cirebon City is dominated by low-lying coastal plains with relatively gentle slopes. This condition affects drainage patterns and organic waste management, as household waste disposal systems are largely dependent on urban facilities and conventional transportation systems. In addition, the city's location, which borders the Java Sea to the north and a water catchment area to the south, means that environmental and domestic waste management have important implications for the quality of the coastal ecosystem and public health.

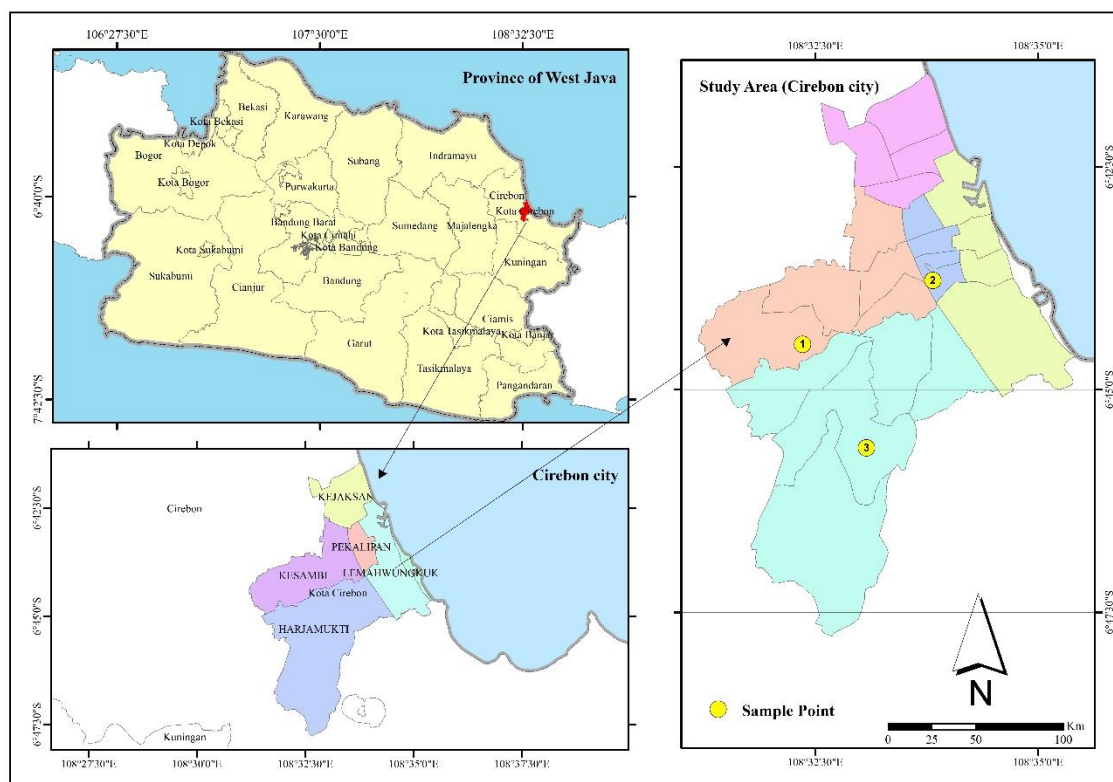


Figure 1. Study area map of Cirebon City, West Java Province, Indonesia, showing five administrative districts and three community-based waste bank sampling points.

Figure 2 shows the waste management system in Cirebon City, which is still dominated by the linear collect-transport-dispose pattern. The community still does not independently sort organic and inorganic waste, so material value has not been returned to the economic cycle, and community involvement is still limited to the collection stage. This condition is in line with research [Ikhlayel \(2018\)](#) which shows that most cities in developing countries face similar problems:

end-oriented waste management systems and a lack of integration of circular economy approaches.

2.2 Data collection

This study employed a mixed-methods research design using a convergent parallel approach. Quantitative and qualitative data were collected concurrently and integrated during the analysis stage to provide a comprehensive understanding of

household organic waste management behavior. The quantitative component consisted of a structured household survey involving 300 respondents to capture statistically representative behavioral patterns, while the qualitative component focused on participatory observation, co-design discussions, and prototype testing conducted through the Design Thinking framework. The number of participants in

the Design Thinking stage was determined based on methodological guidelines suggesting that approximately 30 participants are sufficient for exploratory and participatory research, where depth of engagement and interaction quality are prioritized over statistical representativeness (Hair et al. 2010). This study was conducted in two main stages, as summarized in Table 1.

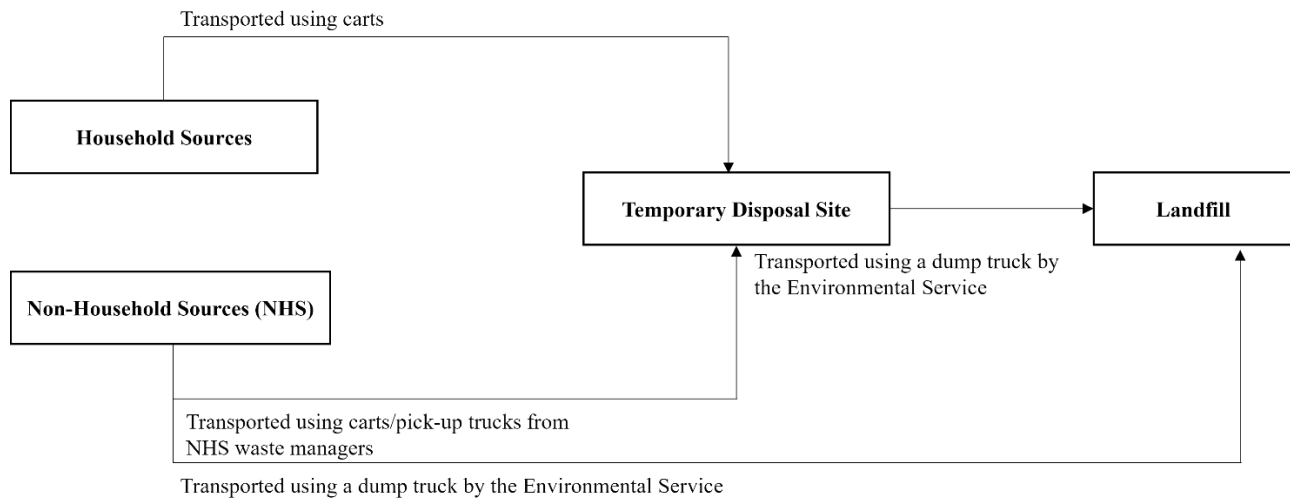


Figure 2. Illustration of the linear waste stream from source to landfill in Cirebon City (adapted from Waste4cange Alam Indonesia, 2022)

Table 1. Research stages

Research stages	Method	Number of participants	Instruments	Main output
Stage I: Behavioral Assessment	Quantitative survey	300 respondents	Likert scale questionnaire	Behavioral data and participation profiles
Stage II: Design Thinking	Participatory design (co-design)	30 households (3 Waste Banks)	Observation, interviews, and prototypes	User-based waste management solutions

2.2.1 Stage I

At this stage, a behavioral environmental assessment was conducted. This approach is in line with the concept of socio-behavioral assessment, which assesses the relationship between awareness, attitudes, and actual actions in the context of household waste management (Bulhões et al., 2023; Treyes et al., 2023; Wilson, et al., 2025). A quantitative survey was conducted with 300 household respondents to evaluate behavioral dimensions related to organic waste management. The number of respondents in this study was determined using the Slovin formula to determine the sample size from a known population. This formula was used to obtain a representative sample size with a certain margin of error. The formula is as follows:

$$n = \frac{N}{1 + N(e)^2}$$

With the following explanation: n=required sample size; N=population size; e=margin of error, set at 6% (0.06) in this study.

Based on data from the Central Statistics Agency (BPS) of Cirebon City in 2023, the population of Cirebon City is 341,980 people. Thus, the sample size calculation is as follows:

$$n = \frac{341.980}{1 + 341.980(0.06)^2} = 277.55 \approx 278$$

$$ni = \frac{N_i}{N} \times n$$

With the following explanation: ni=number of respondents in the i-th subdistrict; N_i=population in

the i -th subdistrict; N =total population of Cirebon City; n =total research sample (300 people).

The sample distribution as shown in Table 2 indicates that respondents were distributed proportionally across the five subdistricts in Cirebon City according to the population of each area. This proportional distribution was intended to ensure that each subdistrict was adequately represented, allowing the data to reflect the social, and geographical diversity of the community. After the number and distribution of respondents were determined, the next step was to develop a research instrument used to measure community behavior towards organic waste management. This instrument was developed in the form of a structured questionnaire using a five-point Likert scale (1=strongly disagree to 5=strongly agree).

The questionnaire indicators were structured into two functional groups based on their analytical purpose. Indicators 1-3 were designed to capture baseline household waste disposal practices and existing organic waste management conditions, including disposal habits, waste separation behavior, and the level of organic waste generation. These indicators were analyzed descriptively to provide an overview of the current waste management situation in Cirebon City.

Indicators 4-8 represent the core behavioral constructs of this study, including awareness and

understanding, participation (actual action), challenges in waste management, organic waste composting practices, and support for circular economy practices. These indicators were subsequently subjected to validity and reliability testing, as well as Spearman's rank correlation analysis, to examine the relationships between behavioral dimensions in household organic waste management. Each statement in the questionnaire was developed based on the results of a literature review and the empirical context of waste management in the Cirebon City, which were then grouped into five main behavioral indicators, namely understanding and awareness, attitudes towards waste management programs, actual practices of organic waste management, willingness to participate, and perceptions of the benefits of the circular economy, as presented in Table 3.

Table 2. Number of samples by district in Cirebon City

No.	District	Population	Number of Samples
1.	Harjamukti	128,778	113
2.	Lemahwungkuk	58,418	51
3.	Pekalipan	29,716	26
4.	Kesambi	78,398	69
5.	Kejaksan	46,670	41
Total		341,980	300

Source: BPS (2024)

Table 3. Measurement indicators

Indicator number	Research indicator	Measurement purpose
4	Understanding and Awareness	Assessing the level of knowledge, awareness, and concern of respondents regarding environmental issues and the negative impacts of poorly managed organic waste.
5	Attitude toward Waste Management Programs	Measuring respondents' acceptance, support, and trust in waste management policies, programs, and activities implemented by the government or local communities.
6	Actual Practices of Organic Waste Management	Evaluating respondents' actual actions in sorting, storing, processing (e.g., composting), and disposing of organic waste on a daily basis.
7	Willingness to Participate	Assessing respondents' readiness, motivation, and willingness to actively participate in organic waste management activities at the household and community levels.
8	Perceived Benefits of Circular Economy	Measuring respondents' views on the potential economic benefits (such as cost savings or the sale value of compost), social benefits (community togetherness), and environmental benefits of implementing circular economy principles.

Before being used in the main study, the questionnaire instrument was tested for validity and reliability to ensure the consistent measurement of behavioral constructs. The validity test was conducted using Spearman's Rank correlation (Spearman's rho) with a total of 30 pilot respondents who had

characteristics similar to the main study population. This test was selected because the data were ordinal (Likert scale) and not normally distributed. The results showed that all statement items had calculated correlation coefficients greater than the critical value ($r=0.361$; $\alpha=0.05$), indicating that all items were valid

and suitable for use in the main study. Instrument reliability was assessed using Cronbach's alpha coefficient. The results showed a Cronbach's alpha value of 0.701 for the five questionnaire items, indicating acceptable internal consistency. All items demonstrated corrected item total correlation values above 0.30, and the Cronbach's alpha value did not increase when any item was deleted, confirming that all indicators were retained for further analysis. (Sullivan and Artino Jr, 2013).

2.2.2 Stage II

This stage was conducted using the Design Thinking (DT) method to explore community needs and design practical solutions for household organic waste management that are appropriate to the social context of Cirebon City. A total of 30 participants were involved in the Design Thinking (DT) stage. Participants were purposively selected from three active Waste Bank communities in Cirebon City, with 10 participants from each location. The selection aimed to ensure the diversity of perspectives, including ordinary residents, Waste Bank members, and Waste Bank managers, who represent different roles and levels of engagement in household organic waste management.

The number of participants was determined based on two considerations. First, previous methodological guidelines suggest that a minimum sample size of approximately 30 respondents is adequate for exploratory and relatively simple analytical models (Hair et al., 2010). Second, in participatory and Design Thinking based research, the emphasis is placed on depth of engagement, interaction quality, and information saturation rather than statistical representativeness. The involvement of 30 participants across three community settings was sufficient to capture diverse behavioral patterns, identify key barriers, and support iterative co-design and prototype testing processes. This approach serves as an innovative framework based on community participation (human-centered approach), which aims to produce a waste management system design that can be directly applied at the household and community levels. The Design Thinking stages applied in this study were adapted from established Design Thinking frameworks consisting of five main phases: Empathize, Define, Ideate, Prototype, and Test (Brenner and Uebernickel, 2016). The following diagram illustrates these stages. The following diagram shows these stages.

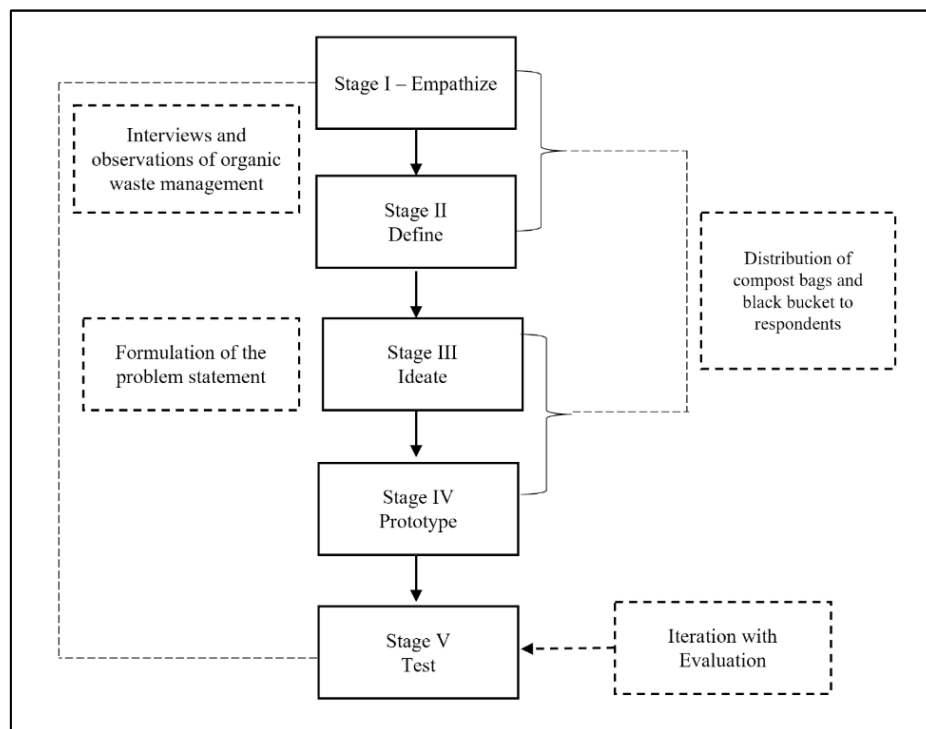


Figure 3. The five stages of the Design Thinking process applied in this study (Empathize, Define, Ideate, Prototype, and Test), showing the iterative participatory process with household respondents.

All stages were carried out participatively by involving 30 respondents from three active Waste Banks in Cirebon City, namely Harjamukti Waste Bank, Lemahwungkuk Waste Bank, and Kesambi Waste Bank, with 10 respondents from each location (Figure 3). The participatory approach in this study not only emphasized community involvement in designing solutions but also ensured that the research was conducted in accordance with academic ethical standards, taking into account the rights, comfort, and confidentiality of participants, with approval from the Gadjah Mada University Research Ethics Committee (Approval Number: KE/UGM/160/EC/2025).

The Empathize stage was conducted through direct observation (shadowing) and in-depth interviews to understand the respondents' interactions with organic waste in their households. The researchers traced the flow of organic waste from the moment it was produced in the kitchen to its disposal at the final disposal site, in order to identify the needs, obstacles (pain points), and habits of the community. The interview results showed that most respondents stored organic waste in plastic bags in the kitchen area, and once full, the waste was disposed of along with other waste without any prior processing. This practice caused various problems, such as unpleasant odors, leachate leaking from plastic bags, and the presence of flies and maggots that disturbed household comfort.

This was followed by the Define stage, which aimed to formulate the main problem statement. The community needs a closed, hygienic, odorless, and easy-to-use organic waste management system that does not add to the workload of households and allows organic waste to be reused as compost. Thus, the problem statement focused on the need for a practical, hygienic, and productive household organic waste management solution. Based on the problem formulation results, the participants and researchers developed a solution sketch. The most promising idea was a two-container system, namely:

1. A black bucket with a lid used as a temporary container in the kitchen,
2. A compost bag used as the main container for the composting process.

Next is the prototype stage, during which researchers provide two containers to each respondent and gave instructions on how to use them. The aim was to test the practicality, cleanliness, and comfort of use in the context of daily household activities. At the prototype stage, the solution design was further developed through the application of a layer system

within the compost bag. This system was designed to support mize the decomposition process while minimizing odors, leachate, and maggot growth. This approach aligns with the findings of [Jihad and Arif \(2024\)](#), who developed aerobic composters based on a layered recycled material system that can stabilizes moisture and reduce ammonia emissions during the composting process.

Research by [Tumanggor et al. \(2024\)](#) also shows that a simple compost bag method with standardized guidelines effectively improves community skills and participation in independent organic waste management. In this study, the bottom layer of the composter was first filled with dry materials such as sawdust, raw rice husks, or charred rice husk with a thickness of approximately 10 cm. This initial layer serves as a leachate absorption pad, aeration support, and a source of carbon-rich material, thereby helping to balance the C/N ratio of the compost mixture. Kitchen organic waste was then added on top of the base layer, and was covered again with a thin layer of dry material. This layering pattern was repeated gradually according to the volume of organic waste produced, so that each input of wet waste was always "trapped" between layers of dry material. [Afla et al. \(2023\)](#) explain that the success of household composting is influenced by the balance between carbon-rich materials (such as husks and sawdust) and nitrogen-rich materials (food scraps), which helps maintain microbial activity and compost temperature stability.

Compost bags have covers. In this study, the covers were not kept tightly closed, but left slightly open, with approximately 20% airflow to maintain oxygen supply and sustain the aerobic decomposition process. This ventilation arrangement was intended to keep the internal temperature of the composter within a warm range, thereby supporting the activity of decomposing microorganisms and suppressing maggot growth. Aeration through ventilation can maintain aerobic conditions in the composter, thereby increasing the optimal internal temperature for aerobic microbes and reducing the chance of unwanted vectors such as insect larvae, from developing ([Amrul et al., 2022](#)). Thus, the layer system method in compost bags not only improves the quality of the composting process but also forms part of a biological control strategy against maggots and other vector pests in household organic waste management.

The next stage is the testing stage, where field trials are conducted through iterative cycles.

Participants (respondents) are asked to provide feedback on the system's effectiveness, odor control capabilities, ease of use, and compost quality. This input is used to refine the system design and evaluate its potential for wider application through the Waste Bank, allowing this iterative process to enable researchers and the community to make continuous adjustments to the system design, resulting in a waste management model that is not only functional but also contextually appropriate to local needs. This approach is in line with the findings of [Ermayendri et al. \(2025\)](#) on the concept of participatory collaboration as a crucial component in developing adaptive solutions where participant feedback becomes part of a continuous improvement strategy in urban waste management.

3. RESULTS

3.1 Socio demographic characteristics and existing conditions of organic waste management

3.1.1 Socio demographic profile of respondents

Understanding socio-demographic characteristics is crucial for explaining organic waste management behavior at the household level.

Based on a survey of 300 respondents in Cirebon City, [Table 4](#) shows that the majority of respondents were women (60.3%), were of productive age (36-55 years, 45.7%), with the dominant occupations being office workers/teachers (37.7%) and housewives (21.3%). Most had an income below IDR 2.5 million (54.3%) and consisted of small to medium-sized families (1-6 household members, 97%).

Table 4. Socio-demographic characteristics of respondents

Demographic background		Frequency	Percentage (%)
Gender	Male	119	39.67
	Female	181	60.33
Age	15-25	60	20.00
	26-35	50	16.67
	36-45	68	22.67
	46-55	69	23.00
	56-65	45	15
	66-75	8	2.67
Occupation	Housewife	64	21.33
	Other	46	15.33
	Merchant	39	13.00
	Farmers	3	1.00
	Office worker/teacher	113	37.67
	Students	35	11.67
Income	>1.5 million	103	34.33
	1.5 million - 2.5 million	60	20.00
	2.5 million - 3.5 million	45	15
	3.5 million - 4.5 million	40	13.33
	> 4.5 million	52	17.33
Number of family members	1-3 people	136	45.33
	4-6 people	155	51.67
	7-9 people	8	2.67
	> 10 people	1	0.33

3.1.2 Gender dimension and role of women in waste management

A total of 60.3% of respondents were women, while 39.7% were men. Female respondents were predominantly involved in household-level organic waste activities, particularly sorting, collecting, and processing organic waste into compost, whereas male participation was more limited and primarily indirect.

3.1.3 Influence of age and household lifecycle

Based on the survey results in Cirebon City ([Table 4](#)), the majority of respondents were in the productive age group (36-55 years). In this study, respondents within this age range showed higher levels of awareness and willingness to participate in household organic waste management compared to younger respondents. This finding is consistent with previous studies ([Tarigan et al., 2020](#)), which report a positive association between age, environmental

awareness, and participation in waste management activities.

In contrast, younger respondents (15-25 years, 20% of the sample) tended to report lower engagement in waste management practices, which may be related to lifestyle patterns and weaker attachment to household management responsibilities. These findings highlight the importance of intergenerational education strategies, particularly through schools and universities, to foster circular economy behavior from an early age.

3.1.4 Occupational and income factors

Occupation and income levels have direct implications for waste management behavior. Office workers and teachers (37.7%) have high environmental knowledge, but time constraints may reduce their level of active involvement. Meanwhile, housewives (21.3%) play a major role in waste sorting at home. Low income (<Rp2.5 million, 54.3%) face challenges in participation due to limited financial resources and waste management facilities (Rois et al., 2020). However, within a circular economy context, low-income groups may have high participation potential if supported by appropriate incentive mechanisms and infrastructure (Gunamantha et al., 2023). This is supported by empirical research demonstrating that economic motivation particularly financial saving motives plays an important role in encouraging household behaviors related to waste reduction and resource utilization (Begho and Zhao, 2023).

3.1.5 Household size and waste generation

The majority of households (51.7%) have 4-6 family members, which implies a higher volume of organic waste generation. As household size increases, the amount of waste generated also rises, making greater collaboration among household members essential for implementing a circular economy-based waste management system. A study in Jakarta shows

that household size is a significant variable influencing sorting behavior and organic waste processing (Pravitasari, 2025).

3.1.6 Current conditions of organic waste management in Cirebon

Organic waste management in Cirebon City remains inadequate and requires significant improvement. Most of the organic waste produced by the community is still disposed of directly in landfills without proper separation or treatment processes at the household level.

Based on a survey of 300 respondents in Cirebon City, organic waste management patterns are still traditional as shown in Figure 4. Figure 4 presents baseline household waste management practices in Cirebon City based on Indicators 1-3, which capture disposal habits, waste separation behavior, and the intensity of organic waste generation prior to behavioral intervention analysis. Most of the community (82%) still relies on a collect and dispose system. Only 21% of respondents always sort organic waste, while 49% never sort it. This pattern shows that organic waste management in Cirebon is still linear and has not yet implemented the principles of reduce, reuse, recycle (3R) to become circular. This condition is similar to the findings of (Ikhlayel, 2018), which states that many developing cities still focus on end-of-pipe systems (collection and disposal to landfills) rather than source processing. Recent research also shows low levels of community participation due to limited sorting facilities and low social motivation (Wijayanti et al., 2023). The lack of facilities such as composters, waste bank infrastructure, and incentive systems has made the community reluctant to participate actively. The results confirm that community participation will increase if there is support in the form of facilities, economic incentives, and clear policies (Viva et al., 2020).

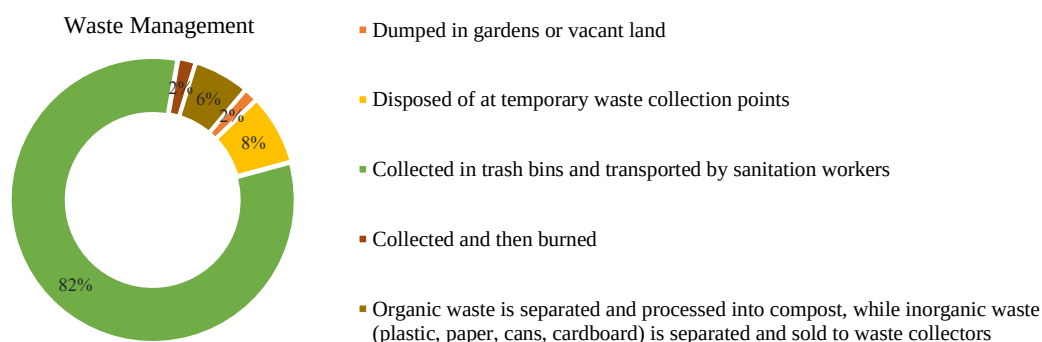


Figure 4. Household waste management practices in Cirebon City, Indonesia based on a survey of 300 respondents.

The results of a survey of 300 respondents in Cirebon City related to organic waste sorting practices are presented in Table 5. Nearly half of respondents (49%) reported that they never sort organic waste,

while 30% indicated that they sort waste occasionally. Only 21% of respondents consistently separate organic waste at the household level.

Table 5. Organic waste sorting data

Response category	Percentage (%)	Interpretation	Implications for organic waste management conditions
Yes (always sorts)	21	Only a small portion of the community consistently separates organic waste.	Active participation is still low, indicating limitations in sorting at source.
Sometimes sorting	30	Some people sort waste but not regularly; it is more situational.	Awareness exists, but the behavior has not yet become a habit; a sustained approach is needed.
Do not sort	49	Nearly half of respondents never sort organic waste.	This indicates the weakness of the existing conditions, so that management still depends on the collect-transport-dispose system to landfills.

As shown in Table 5, although some respondents are aware of the importance of separating organic waste, the practice has not yet become a habit. This data shows that although some people are aware of the importance of separating organic waste, the practice has not yet become a habit. As a result, organic waste management is hampered, and the implementation of the program in the field has not

been running as it should. Figure 5 shows that most respondents exhibit high levels of awareness regarding organic waste management, with the “very strong” and “strong” categories dominating the distribution. In contrast, fewer respondents fall into the “weak” and “very weak” categories, indicating generally favorable knowledge and understanding among the surveyed population.

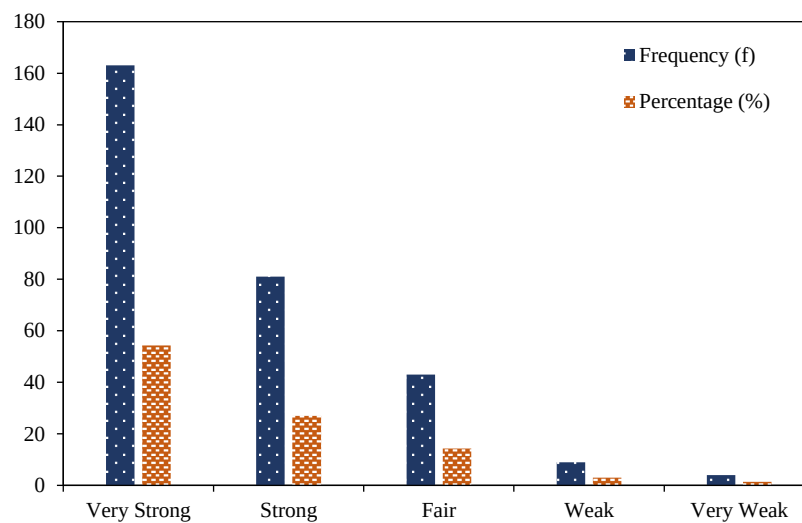


Figure 5. Average levels of respondents' awareness and understanding of household organic waste management

The graph in Figure 5 shows that the level of public awareness and understanding of organic waste management is high. Most respondents (around 58%) fall into the very strong awareness category, followed by 26% in the strong category, 11% in the moderate category, and only a small portion (around 5%) in the weak and very weak categories. These results indicate that most people understand the importance of organic waste management for the environment, especially in

the context of reducing household waste volume and supporting the potential implementation for a circular economy.

3.1.7 Challenges in implementing circular economy-based waste management

The biggest challenges in implementing a circular economy-based organic waste management system in Cirebon City include three main aspects:

- a) Limited infrastructure

The absence of processing facilities such as household composters, separate organic waste collection points, and incentive facilities remains a major obstacle.

b) Socio-cultural aspects

The community's mindset, which still views waste as a burden rather than a valuable resource, slows down the adoption of a circular economy system.

c) Policy and governance

The absence of specific regulations that encourage waste valorization and provide economic incentives hinders implementation in the field.

d) This situation is in line with research findings in various Indonesian cities that point to weak governance, poor inter-agency coordination, and a lack of technological innovation as the main causes of

low effectiveness in waste management (Listiningrum, 2023).

3.2 Results of Spearman's Correlation analysis

Spearman's rank correlation analysis was used to measure the relationship between indicators of community behavior in organic waste management in Cirebon City. This test was chosen because the data obtained were on a Likert scale. As shown in Table 6, several indicator pairs exhibit positive and statistically significant correlations at the 99% confidence level ($p < 0.01$). The strongest relationship was observed between awareness and understanding (Indicator 4) and willingness to participate (Indicator 7) ($\rho = 0.500$), indicating that higher public awareness is associated with greater community participation in household organic waste management.

Table 6. Spearman's rank correlation analysis

	Indicator 4: Awareness (knowledge and understanding)	Indicator 5: Participation (actual action)	Indicator 6: Challenges in waste management	Indicator 7: Organic waste composting	Indicator 8: Support for circular economy practices
Indicator 4: Awareness (knowledge and understanding)	—	0.335	0.258	0.500	0.395
Indicator 5: Participation (actual action)		—	0.209	0.287	0.215
Indicator 6: Challenges in waste management			—	0.255	0.332
Indicator 7: Organic waste composting				—	0.451**
Indicator 8: Support for circular economy practices					—

**Correlation is significant at the 0.01 level (two-tailed)

Spearman's rank correlation analysis was conducted using Indicators 4-8 to examine relationships among the main behavioral constructs. As shown in Table 6, several indicator pairs exhibit positive and statistically significant correlations at the 99% confidence level ($p < 0.01$). The strongest relationship was observed between awareness and understanding (Indicator 4) and willingness to participate (Indicator 7) ($\rho = 0.500$; $p < 0.01$), indicating a strong association between public awareness and community participation in household organic waste management. This suggests that direct experience in waste management plays an important role in shaping awareness of the circular economy (Gunamantha et al., 2023). This relationship is further illustrated in Figure 6, which shows a positive trend between

awareness and understanding scores and willingness to participate.

As shown in Figure 6, awareness and understanding are positively associated with willingness to participate in household organic waste management. The scatter plot indicates an upward trend, which is supported by a significant Spearman correlation ($\rho = 0.395$; $p < 0.01$). Overall, these results indicate that all components of behavior; awareness, attitude, practice, participation, and economic perception have mutually supportive relationships and form an integrated behavioral system. This aligns with the findings of Utomo et al. 2021 which state that the success of household waste management is significantly influenced by a combination of cognitive factors (knowledge and awareness), affective factors

(attitudes and motivation), and instrumental factors (participation and perceived benefits). Thus, the results of this correlation test reinforce that circular economy-based organic waste management at the

household level requires a multidimensional approach that integrates environmental education, social support, and community economic empowerment.

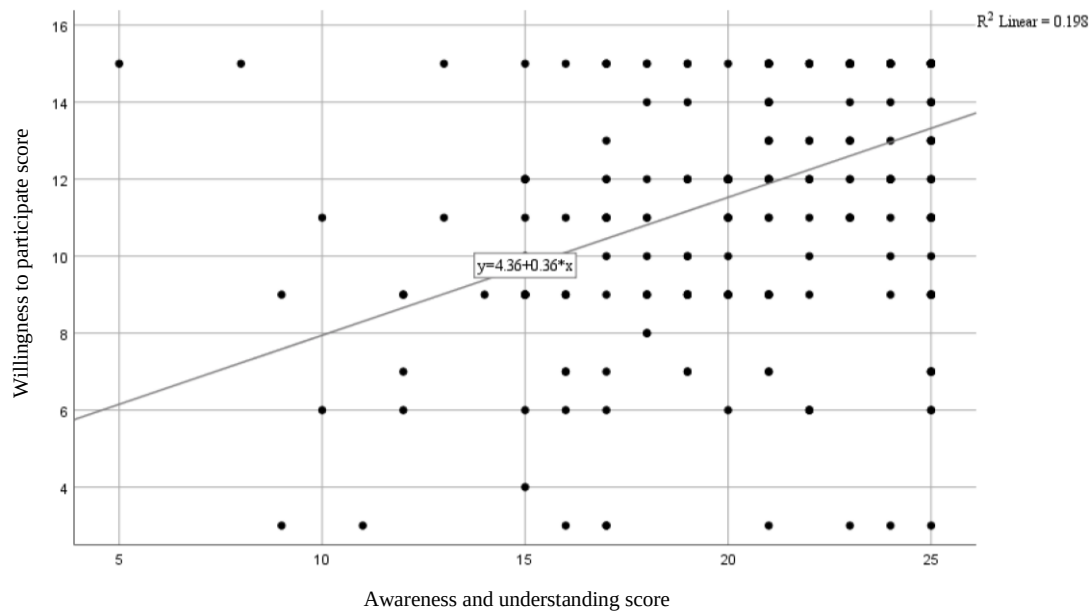


Figure 6. Relationship between awareness and willingness to participate in household organic waste management (Spearman's correlation).

3.3 Integration with the design thinking approach

The quantitative results formed the basis for the DT stages applied to 30 respondents across three Waste Bank locations. Based on the survey results, the two aspects with the highest scores (awareness and participation) were used as social capital, while the two aspects with low scores (attitudes and economic perceptions) became the focus of design interventions. The five behavioral indicators were mapped onto the five main stages of DT presented in Table 7.

After a series of DT sessions, the next step was to analyze the challenges in using the prototype as a basis for further iteration through participatory collaborative process sessions. This process is important because the initial prototype is evaluated not only from a technical functionality perspective, but also from the end-user's perspective, to ensuring that the developed solution is aligned with the needs and local context of the community (Leal Filho et al., 2024). In the literature on design-based innovation methodologies, an iterative approach that actively involves participants in participatory workshops enables researchers and stakeholders to re-evaluate initial assumptions, identify operational obstacles, and generate design improvements based on users' real experiences (Denecke et al., 2025).

The ongoing participatory and collaborative process have been recognized as an important practice in DT to support the development of relevant and sustainable solutions, as participants not only provide feedback but also actively contribute to refining prototypes based on their own socio-environmental context. Through this approach, prototype iterations become more meaningful because each design revision is informed by empirical insights gained from participant involvement in activities that reflect their daily routines. This method aligns with DT principles that emphasize solution development through direct user involvement, the exploration of real needs, and continuous iterative feedback to strengthen the relevance of solutions to the problems faced by the community (Hoolohan and Browne, 2020).

Furthermore, this collaborative workshop process not only produces technically improved designs but also strengthens the community's shared understanding, attitudes and behavior towards organic waste management. This is important in the context of the transition to a circular economy, as changes in community behavior are a determining factor in the successful adoption of new practices (Barile and Kelestyn, 2023). Thus, participatory feedback-based iterations ensure that prototypes are not only tested as

research objects but also co- developed together with the community, so that the final solution is more more adaptive, responsive, and potentially more likely to be accepted by the community in the long term.

Based on observations at three research sites, the main challenges in household organic waste management, as shown in [Table 8](#), relate to container

capacity, moisture control, and rodent infestation that can puncture composters. This analysis emphasizes the importance of empathy-based composter design, focusing on functional needs (aeration, moisture, and hygiene) and user experience (ease of use, cleanliness, and economic benefits).

Table 7. Design thinking process steps

Design thinking stages	Activity focus	Relevant behavioral indicators	Key outcomes
Empathize	Exploring empathy for respondents' experiences in producing organic waste from generation to disposal through in-depth interviews and observations at three Waste Bank locations.	Understanding and Awareness (Ind.4)	Most respondents store organic waste in plastic bags in the kitchen, then dispose of it together with inorganic waste without sorting or processing.
Define	Formulating problem statements based on pain points and insights to define the community's primary needs.	Attitude toward the Program (Ind.5)	Residents need a household organic waste management system that is: - is closed and hygienic, - does not cause odors, - is easy to operate, - does not increase the workload for households, - enables the reuse of organic waste as compost.
Ideate	Conducting co-creation workshops to generate various alternative solutions.	Willingness to Participate (Ind.7)	Agreed on a solution design in the form of a dual-container system consisting of: 1. A black bucket as a temporary storage container in the kitchen, and 2. A compost bag as the main container for the composting process.
Prototype	Designing and distributing waste management tools for testing.	Practical Application (Ind.6)	Respondents used compost bags at home for 2 months
Test	Evaluating the effectiveness of prototypes on residents' behavior and perceptions.	Perception of Economic Benefits (Ind.8)	Participation increased, perceptions of economic benefits rose by 23%, and waste sorting became a routine practice as people became accustomed to it.

Table 8. Challenges in organic waste sorting during the prototype stage

Aspect	Seruni Waste Bank (Jagasatru)	Carangka Runtah Waste Bank (Harjamukti)	Sukses waste bank (Karyamulya)	Thematic analysis and design insights
Initial management practices	Waste is initially collected in plastic bags before being transferred to bins.	Some residents directly put waste into buckets and add dry materials.	Many residents place organic waste directly into the composter without using a temporary bucket.	A flexible container design that matches the volume of household waste is needed to encourage source separation.
Main problem faced	Unpleasant odors caused by the accumulation of organic waste	Odors are relatively reduced by the addition of sawdust; however, leachate is still present.	High moisture levels and tightly closed containers lead to odor and maggot proliferation.	Adequate aeration and moisture control are critical factors for successful household composting.
Local adaptation efforts	Placing buckets in open areas to reduce odor.	Sawdust is used as a natural absorbent material to control moisture and odor.	Residents attempt to reduce impacts by drying waste before disposal or utilizing maggots as animal feed.	Existing local adaptation practices should be integrated into solution design to enhance effectiveness.
Key pain points	Limited bucket capacity and poor hygiene conditions.	Leakage continues to occur despite the use of dry materials.	Composters fill up quickly, with many maggots.	Households require closed organic waste management containers to improve hygiene and comfort.

Table 8. Challenges in organic waste sorting during the prototype stage (cont.)

Aspect	Seruni Waste Bank (Jagasatru)	Carangka Runtah Waste Bank (Harjamukti)	Sukses waste bank (Karyamulya)	Thematic analysis and design insights
User priority needs	Need for a large-capacity, odor-resistant container that is easy to clean.	Need for a container with controlled air ventilation and a simple drainage system.	Need for a compost bin that allows waste compaction and controlled aeration.	Applying a user-centered design principle, the system must control odor, leachate, and maggots without increasing household workload.

Field test results, as presented in [Table 9](#), show that the type of dry material (carbon source) has a significant effect on the effectiveness of the household composting process. Of the three materials tested, sawdust, charred rice husk, and raw rice husks, sawdust showed the best performance in maintaining the stability of the biological process and the quality of the final compost. The sawdust composter maintained an optimal temperature of 38-42°C during the thermophilic stage, stable moisture conditions, and produced dark brown compost with a neutral earthy odor in six weeks. This indicates that sawdust has an ideal C/N ratio and porosity, thereby supporting aerobic microbial activity and accelerating decomposition ([Kaur et al., 2019](#)).

On the other hand, charred rice husk, although effective in reducing odor and leachate, has a disadvantage in terms of water absorption. The composting process runs more slowly because moisture quickly falls below the ideal threshold, requiring the addition of water or fresh organic material to maintain microbial activity ([Bhatia et al., 2013](#)). Meanwhile, raw rice husks provide good aeration but are unable to absorb excess moisture. These conditions cause leachate formation, odor, and high maggot populations, especially in the third to fourth week of observation. Although some residents use maggots as animal feed, these conditions indicate an imbalance in the aerobic decomposition process that can inhibit compost maturity.

Table 9. Field findings: User needs and behavioral barriers in compost bag utilization

Location/Waste Bank	Habits and challenges in bucket use (Pre-compost)	Challenges and needs in compost bag use (Composting Stage)	Design insights and initial recommendations
Seruni (Jagasatru)	The majority of respondents store organic waste in plastic bags before transferring it to buckets. Main complaints: odor, leachate, and concerns about rats.	Some composters experience leaks due to rat bites and strong-smelling leachate. Respondents complain about wet conditions and maggot infestations.	Composters need good ventilation, stronger materials to resist rodents, and a leachate control system. Simple technical training is needed to maintain the dry-to-wet ratio.
Carangka Runtah (Harjamukti)	Most respondents added sawdust to the bucket to reduce odor and moisture. Some still delayed waste transfer.	Most users are satisfied and do not experience strong odors. A minor challenge is slow waste addition due to small volumes.	The use of dry materials is effective; it can be used as a best practice model. A medium-capacity composter is needed to accommodate the volume of household waste.
Success (Karyamulya)	Many respondents do not use buckets due to their small capacity; they prefer large plastic containers. Some use them for inorganic waste.	Main issues: odor, maggots emerging during the rainy season, and the composter filling up quickly. Some residents use the maggots as animal feed.	The composter design needs a cross-ventilation system and humidity control, as well as an automatic leachate removal mechanism. There is a need for socialization of the frequency of filling and periodic maintenance.

In general, these results confirm that the physical characteristics of dry materials determine the efficiency of household composting systems, especially in terms of aeration, moisture, and odor control. From a Design Thinking perspective, these findings form the basis of the Define and Ideate stages, namely design of

household composters with cross-ventilation systems, automatic moisture control, and capacities tailored to the needs of urban households. This approach is in line with the principles of human-centered design in environmental management, where technical solutions must consider user behavior, comfort, and ease of

maintenance (Kim et al., 2021). The integration of field results with a participatory design approach shows that the community's direct experience in using composters can increase engagement, environmental awareness, and the perceived economic benefits of circular economy practices.

4. DISCUSSION

4.1 Behavioral interpretation of household waste management practices

As shown in Table 4, household organic waste management in Cirebon City is strongly influenced by gender roles and daily domestic responsibilities. The predominance of women respondents reflects their central role in sorting, collecting, and processing organic waste at the household level. This finding is consistent with evidence from developing countries showing that women can play a central role in community-based waste management and that their empowerment and active participation can contribute to broader improvements in waste management systems (Estrada et al., 2023). However, the lower participation of men suggests the need for more inclusive, gender-sensitive community engagement strategies. In this context, Waste Bank programs can strengthen women's roles as agents of change while encouraging greater male participation through targeted community-based interventions.

4.2 Awareness participation gap and theory of planned behavior

Despite relatively high levels of awareness regarding the importance of organic waste management, actual household participation remains limited. This awareness-participation gap indicates that knowledge alone is insufficient to drive behavioral change. According to the Theory of Planned Behavior (TPB), behavior is influenced not only by attitudes, but also by subjective norms and perceived behavioral control.

In this study, although respondents generally showed positive attitudes toward organic waste management, participation was constrained by weak social norms and limited perceived control. The lack of sorting facilities, composting infrastructure, and clear incentives reduced households' confidence in their ability to manage organic waste effectively. The application of Design Thinking (DT) helped address these barriers by enhancing perceived behavioral control through user-centered composting solutions and participatory co-design processes. By involving

households directly in problem identification, solution design, and prototype testing, the intervention strengthened both individual agency and collective norms, demonstrating the potential of Design Thinking to bridge the gap between awareness and sustained participation in household-level circular economy practices.

4.3 Design thinking as a participatory intervention tool

In this study, Design Thinking functioned not only as a problem-solving framework but as a participatory intervention tool that facilitated behavioral change in household organic waste management. By emphasizing empathy, collaboration, and iterative learning, the Design Thinking process enabled households to identify barriers, co-create solutions, and test practical interventions within their daily routines. This participatory approach strengthened perceived behavioral control by allowing households to develop composting solutions aligned with their capacities, space constraints, and time availability, thereby reducing psychological and practical barriers to participation. Collective activities during the Design Thinking stages also fostered shared norms and peer learning, reinforcing pro-environmental behavior at the community level.

4.4 Implications for circular economy implementation

The findings of this study highlight important implications for the implementation of the circular economy at the household and community levels. While circular economy policies often emphasize technological and infrastructure-based solutions, this study demonstrates that behavioral and social dimensions are equally critical. The persistence of linear waste management practices, despite relatively high awareness, indicates that circular economy implementation cannot rely solely on information provision or technical interventions. By integrating Design Thinking as a participatory intervention, this study shows how circular economy principles can be operationalized through user-centered solutions that align with local capacities, routines, and social contexts.

At the community level, the involvement of Waste Banks as participatory platforms and catalysts for circular economy practices. Beyond waste collection, Waste Banks can function as spaces for learning, co-design, and experimentation, enabling

households to actively engage in resource recovery. This decentralized and inclusive approach is particularly relevant for medium-sized cities in developing countries with limited institutional capacity and infrastructure.

4.5 Policy and practical implications

The findings of this study suggest several policy and practical implications for strengthening household based organic waste management within a circular economy framework. At the policy level, local governments should move beyond infrastructure-centered approaches and integrate participatory and behavior-oriented strategies into waste management programs. Embedding Design Thinking within community-based initiatives, such as Waste Bank programs, can enhance public engagement by aligning interventions with household capacities, routines, and social contexts.

From a practical perspective, Waste Banks can be repositioned as platforms for learning and co-creation rather than solely as waste collection facilities. Facilitating co-design activities, hands-on composting demonstrations, and prototype testing can help households build skills and confidence, thereby increasing sustained participation. The use of simple, low-cost, and locally available materials can further reduce technical and financial barriers. In addition, gender-sensitive and inclusive engagement strategies are essential to strengthen social norms and collective responsibility. Overall, the proposed approach offers a scalable and context-sensitive model that can be adapted by other medium-sized cities transitioning from linear waste management systems toward a circular economy.

5. CONCLUSION

This study demonstrates that integrating Design Thinking into household organic waste management effectively supports behavioral change and facilitates the implementation of circular economy principles at the local level. The participatory and user centered approach successfully transformed environmental awareness into concrete action, increased community participation, and improved perceptions of the economic benefits of organic waste management. Field testing confirmed that simple, locally available materials, particularly sawdust enhanced household composting performance. This study contributes by positioning Design Thinking as both a behavioral assessment and participatory intervention tool in

household-level circular economy implementation. However, the research is limited to a single urban context and a relatively short intervention period. Future studies should expand the analysis to multiple cities and adopt longitudinal designs to assess long term behavioral change and explore the integration of smart composting systems.

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AUTHOR CONTRIBUTIONS

Experimental run, data Collection, Writing-original draft: Zakiyah Amini; supervision, Conceptualization, methodology, investigation, data curation: Lilik Sutiarso; Supervision, formal analysis, visualization: Ngadisih; Supervision, validation, data curation: Chandra Setyawan; Consultation on environmental aspects: Latifah Abd Manaf; Supervision, project administration: Joko Nugroho Wahyu Karyadi; Supervision Writing, review and editing: Dwi Purnomo.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Strategic Framework for Driving Thai Universities toward Net-Zero Emission: A Case Study of Khon Kaen University

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ABSTRACT

The transition of higher education institutions toward carbon neutrality has become an important component of national climate strategies. In Thailand, although several universities have begun conducting greenhouse gas (GHG) inventories, significant gaps remain in Scope 3 accounting, monitoring systems, and strategic planning frameworks that support long-term decarbonization. This study develops an integrated strategic framework to guide universities toward net-zero pathways, using Khon Kaen University (KKU) as a case study. A mixed-methods approach was employed, combining a systematic literature review, gap analysis, emissions clustering, and design-factor synthesis aligned with international standards, including the IPCC Guidelines, the GHG Protocol Corporate Standard, and ISO 14064-1. Data from Thai university reports and national emission factors were analyzed to classify institutions using hierarchical clustering based on energy intensity, emission intensity per student, sequestration capacity, and commuting emissions. The results reveal that Scope 3 emissions—particularly commuting and procurement—remain insufficiently reported across many institutions, limiting comparability but representing a major mitigation opportunity. The study proposes a University Net Zero Planning Tool that integrates emissions inventories, clustering-based benchmarking, and a design-factor matrix linking emission drivers to prioritized interventions. Application to KKU demonstrates both high operational emissions and substantial land-based sequestration potential. The framework offers a transferable decision-support model for universities in developing-country contexts seeking structured pathways toward carbon neutrality and net-zero targets.

HIGHLIGHTS

- Framework combining a systematic review and clustering to chart net-zero paths.
- Highlights gaps in Scope 3 emissions and MRV that hinder carbon reduction.
- Groups universities into four clusters based on energy, transport, and waste.
- Synthesizes intervention factors and strategic variables into a planning tool.
- Applies the framework to Khon Kaen University and propose a net-zero path.

1. INTRODUCTION

Climate change is one of the most urgent crises of the 21st century, disrupting economies, ecosystems, and societies. The accumulation of greenhouse gases (GHGs), primarily carbon dioxide, accelerates global warming and amplifies vulnerabilities. The Paris Agreement (UNFCCC, 2015) set a target to limit global temperature rise to well below 2°C, with efforts to remain within 1.5°C above pre-industrial levels. Meeting these goals requires participation beyond governments, extending to higher education

institutions (HEIs), which play a vital role in sustainability transitions (Husic, 2024).

Universities are increasingly conceptualized as “campus-as-city” systems, with interlinked domains of energy, mobility, waste, water, and land use (Kohl et al., 2022; Abo-Khalil, 2024; Naaman et al., 2024; Buntornwon and Kumphong, 2022; Filho et al., 2023). They act both as contributors to emissions and as testbeds for low-carbon solutions. Recent studies have reinforced this dual role, showing how systematic frameworks can guide zero-carbon planning. For

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example, Wang et al. (2023) proposed a systematic design framework for zero-carbon campuses that emphasizes cross-domain integration, while Islam et al. (2023) highlighted campus-based zero-carbon action plans as accelerators of citywide decarbonization. Similarly, Paredes-Canencio et al. (2024) reviewed the carbon footprints of higher education institutions globally, underscoring persistent gaps in Scope 3 emissions and MRV systems.

In Thailand, several universities have begun to articulate institution-level climate targets and campus sustainability programs. For example, Chulalongkorn University has publicly communicated a net-zero GHG ambition by 2050, while Mahidol University has articulated a “9-to-Zero” pathway aiming at net-zero emissions by 2030. Some institutions have also begun developing digital platforms for monitoring their carbon footprints. However, no prior study integrates clustering and design-factor synthesis. Despite this momentum, common constraints remain across the sector: Scope 3 categories are often incomplete (especially commuting and procurement), monitoring systems are fragmented across units, and institutions lack a consistent benchmarking framework aligned with national targets of carbon neutrality by 2050 and net zero by 2065 (ONEP, 2021). This study responds to calls for more robust MRV integration (Helmerts et al., 2021; Lin et al., 2024) and financial feasibility assessments (Li and Jia, 2022). It contributes both theoretically and practically to pathways toward carbon-neutral universities.

Against this backdrop, our study contributes a Thai-contextualized planning framework that integrates (i) a structured synthesis of global evidence, (ii) driver-based clustering to reflect institutional heterogeneity, and (iii) an MRV-ready set of design factors and strategic variables that can be operationalized as a replicable tool for Thai universities beyond a single case.

2. METHODOLOGY

2.1 Research design

This study employed a mixed-methods research design (Okoro, 2023), integrating both qualitative and quantitative approaches to ensure methodological rigor and practical relevance. The research framework, shown in Figure 1, was organized into seven sequential phases. The first phase involved a systematic literature review (SLR) to establish theoretical foundations and identify best practices

worldwide. Next, a gap analysis was conducted to pinpoint methodological and contextual gaps relevant to Thai universities. The third phase synthesized design factors by pinpointing key variables influencing greenhouse gas (GHG) emissions and strategic planning. In the fourth phase, a university clustering approach grouped institutions into comparable categories based on size, functions, and emission profiles. The fifth phase identified GHG drivers and conducted a SWOT analysis to assess institutional strengths and weaknesses. Building on these insights, the sixth phase developed a process template to serve as a replicable roadmap for universities seeking to achieve net-zero targets. Finally, the framework was tested through a case study of Khon Kaen University (KKU), confirming its robustness and relevance. Overall, this design ensures that the study is grounded in global theory while being tailored to the specific context of Thai higher education.

2.2 Systematic literature review

This review followed the PRISMA 2009 guidelines and Kitchenham's protocol, covering Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Peer-reviewed studies (2000-2025) on GHG accounting, net-zero pathways, and sustainability frameworks were synthesized, highlighting methods such as the ecological footprint for low-carbon campuses (Zheng et al., 2021) and emission-reduction strategies in higher education institutions (Aghamolaei and Fallahpour, 2023).

Universities are increasingly seen as ‘small-scale models of cities,’ serving as testing grounds for low-carbon transitions (Guerrieri et al., 2019). This campus-as-city viewpoint positions higher education institutions as microcosms of urban sustainability, where infrastructure transitions and urban-metabolism flows across energy, water, materials, and waste can be examined through integrated operations, infrastructure, and governance (Kennedy et al., 2011; Bulkeley et al., 2014). Empirical examples show a variety of methodologies: assessments of energy, transportation, and waste in Indonesian universities (Ridhosari and Rahman, 2020); carbon sequestration from campus green spaces in the U.S. (Fox et al., 2020); and comparative studies of retrofitting versus zero-energy buildings in Europe and the U.S. (Del Borghi et al., 2021). These highlight the importance of context-sensitive approaches to decarbonization.

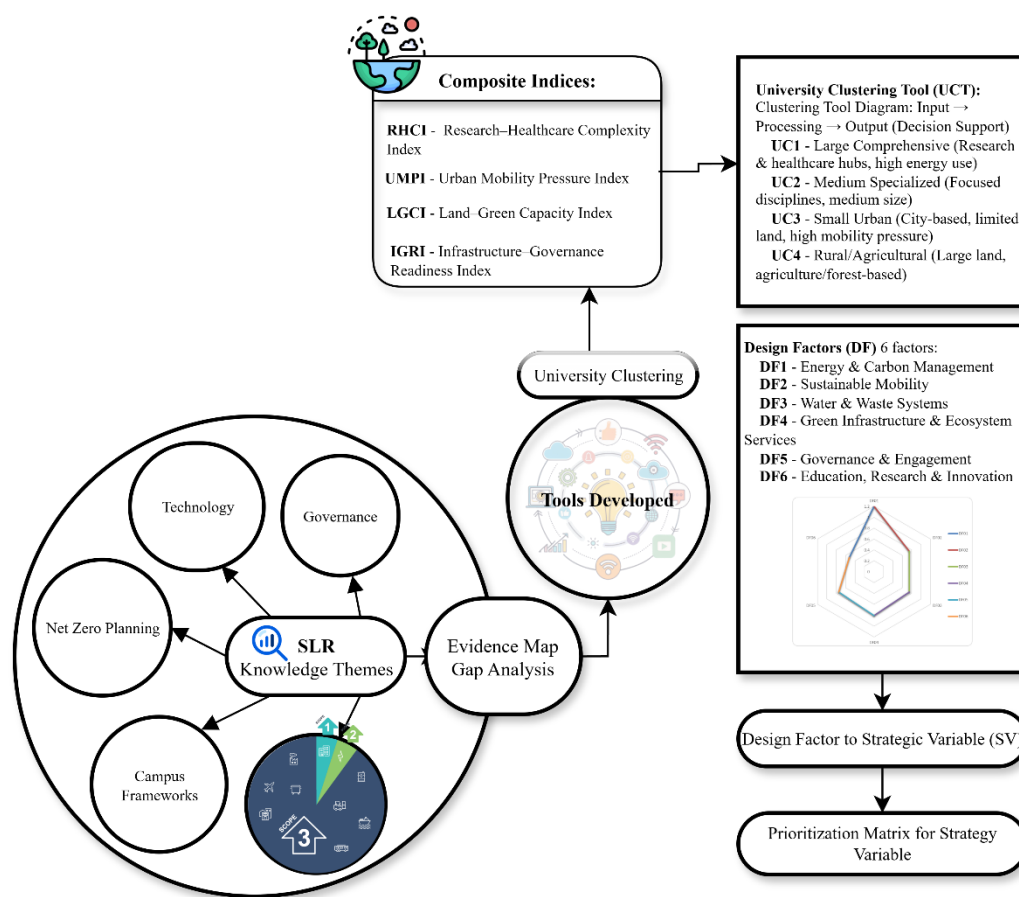


Figure 1. Research design diagram

Systematic reviews offer deeper insights: Zubair et al. (2023) provided structured CO₂ measurement frameworks; Guerrieri et al. (2019) emphasized the role of universities as transitional hubs in urban decarbonization; and nature-based strategies that incorporate green and blue infrastructure were identified as crucial for resilience (Depietri and McPhearson, 2017; Wang et al., 2022).

The SLR procedure and thematic distributions are summarized in Table 3. To strengthen relevance for developing country contexts, we additionally coded studies by data availability and MRV maturity, highlighting recurring constraints in Scope 3 data collection and verification capacity.

Taken together, the evidence confirms that universities act as innovation hubs for sustainability, supporting the clustering and comparative approach used in this research. This combined knowledge directly contributes to the study's goal: to develop and test a framework to evaluate institutional strengths and weaknesses and guide strategic efforts toward net-zero universities.

2.3 Data collection and analysis

Quantitative data were collected from institutional reports, including the Thailand Greenhouse Gas Management Organization (TGO) and the Provincial Electricity Authority (PEA). Indicators covered energy consumption, fuel use, waste generation, green space, and commuting surveys. Cluster analysis was performed using Ward's method, validated with the Calinski-Harabasz index. Factor analysis was carried out using PCA with varimax rotation.

For the clustering analysis (Table 1), we compiled an institutional dataset covering N Thai universities (N=11) for the fiscal year 2012-2020. The clustering variables were selected to represent (i) operational scale, (ii) energy and mobility pressures, and (iii) mitigation potential, and included: electricity use intensity (kWh/m²·year), total organizational emissions (tCO₂e/year), emission intensity (tCO₂e/population·year), campus area (ha), and a sequestration indicator (tCO₂e/year) derived from a green-land inventory. All continuous variables were

z-standardized prior to clustering to avoid scale dominance. Hierarchical agglomerative clustering was conducted using Ward's linkage with Euclidean distance. The number of clusters (k) was determined

by maximizing the Calinski-Harabasz index and cross-checking against silhouette scores shown in [Table 2](#), yielding k=4 as the most parsimonious and statistically supported solution.

Table 1. Dataset, variables, and clustering methodology

Parameter	Technical description
Sample Size (N)	11 Higher Education Institutions (HEIs)
Time Period	2012-2023 (Based on availability of CFO reports)
Primary Variables	Scope 1, 2, 3 Emissions; Total Population; Campus Area; Hospital Dummy
Composite Indices	RHCI, UMPI, LGCI, IGRI (Derived from physical and emission data)
Data Source	Institutional Sustainability Reports, CFO Research Papers, TGO Database
Standardization	Z-score Transformation (Mean=0, Std. Dev=1)
Distance Metric	Euclidean Distance
Clustering Algorithm	Ward's Hierarchical Clustering Method
k Selection Criteria	Calinski-Harabasz Index (CHI) and Average Silhouette Coefficient
Missing Data Handling	Scope 3: Group Mean Imputation based on Peer Cluster Characteristics

Organizational and operational boundaries follow the GHG Protocol. Emissions are reported by Scope 1-3 and by major activity categories. Emission factors were sourced from national factors and complemented by IPCC guidance where local factors were unavailable. The reporting structure and data-quality statements follow the ISO 14064-1 standard.

Because Scope 3 reporting is not uniformly available across institutions, we separated the analysis

into (i) a core clustering model using variables with complete (or near-complete) coverage across universities, and (ii) an extended clustering model incorporating Scope 3-related indicators only for the subset with reported data. We report the core model as the primary classification for national benchmarking and discuss the implications of Scope 3 data gaps as a limitation and a source of uncertainty.

Table 2. Cluster validity Indices across k-values

Number of clusters (k)	Calinski-Harabasz Index (CHI)	Average Silhouette score	Cluster interpretation
2	16.45	0.41	Poor separation; High intra-cluster variance
3	21.12	0.52	Significant overlap between Regional and Urban groups
4	28.7	0.61	Optimal; Best structural representation
5	24.35	0.54	Overfitting; Identifying single-member clusters

2.4 Tool synthesis process

Building on the structured synthesis steps outlined in [Figure 1](#), we created an integrated planning tool. The synthesis process involved (i) extracting design factors from both international and local literature, (ii) consolidating indicators from emission accounting protocols, (iii) mapping these indicators into functional areas (energy, mobility, waste, land, governance), and (iv) developing a Decision Support Template that links GHG sources, metrics, and interventions. The process was iterative, including expert validation workshops and pilot testing with institutional data. The result is the University Net Zero Planning Tool, which allows for clustering

universities by profile, quantifying their Scope 1-3 emissions, and identifying feasible interventions.

Methodologically, we follow the GHG Protocol to define organizational and operational boundaries and classify emissions into Scopes 1-3, while calculation and reporting requirements are structured in accordance with ISO 14064-1. Emission factors and methodological choices are aligned with IPCC guidance and nationally endorsed factors where available. This standards-based approach strengthens comparability and supports third-party verification and future MRV system integration.

Strategic Variables (SVs) were defined as actionable institutional levers mapped to each Design

Factor (DF) domain and GHG scope (Scope 1-3). To ensure reproducibility, each SV was quantified through a two-step procedure. First, SV scores were derived from a structured multi-criteria rating exercise in which experts assessed (a) expected mitigation impact, (b) implementation feasibility, and (c) time-to-delivery. Criterion weights were defined a priori, and the composite SV score was calculated as a weighted sum and then normalized within each DF domain to enable comparison across domains.

Second, the potential GHG reduction for each SV (tCO₂e/year) was estimated using activity data and emission factors consistent with the defined system boundary. For technology-based actions (e.g., PV, retrofits, EV fleets). For governance and behavioral SVs (e.g., procurement policies, travel management), reductions were estimated using conservative uptake scenarios and sensitivity ranges.

2.5 Case study selection

KKU was selected for its size (880 hectares), diverse operations, and its declared net zero 2040 roadmap. The choice is important for three reasons. First, it is among the largest regional universities in Thailand, functioning like a micro-city with its own hospitals, dormitories, academic units, and transportation systems. Second, its net zero 2040 goal offers an ambitious standard for other Thai institutions. Third, KKU's large green spaces and sequestration potential (~18,000 tCO₂e/year) make it well-suited for testing the balance between emissions and offsets. These factors align with recommendations from global reviews emphasizing the importance of diverse campus profiles for validating net-zero frameworks (Paredes-Canencio et al., 2024; Wang et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Literature review outcomes

Out of 5,400 initial studies, 525 met the criteria. Dominant themes were carbon accounting (40%), campus frameworks (25%), net-zero planning (20%), technology and innovation (10%), and governance (5%), as shown in Table 3. These align with recent reviews (Paredes-Canencio et al., 2024), which highlight the urgent need to expand Scope 3 coverage and establish MRV standards. Research gaps remain, especially in integrating digital MRV tools (Helmerts et al., 2021) and ensuring feasibility through financial analysis (Li and Jia, 2022).

Tree-based carbon sequestration is a significant yet often under-evaluated part of campus greenhouse gas (GHG) inventories. A study at the University of Georgia estimated the carbon stored in live trees on its main campus, showing measurable reductions in institutional emissions (Fox et al., 2020). This underscores the importance of the Infrastructure and Green Ratio Index (IGRI), developed within our clustering framework, which highlights the role of green cover in enhancing carbon balance. For agricultural and suburban universities, this factor is especially critical, as larger campus landscapes offer a unique chance for nature-based sequestration strategies.

To improve the clustering framework, four synthetic driver indices were created to represent the structural emission factors of universities shown in Figure 2. Shown: Research and Healthcare Intensity (RHCI), University Mobility Pressure Index (UMPI), Laboratory and Governance Carbon Intensity (LGCI), and Infrastructure and Green Ratio Index (IGRI). These indices help distinguish university clusters by highlighting different emission profiles. For example, urban flagships often exhibit higher UMPI and LGCI scores due to commuting pressures and intensive laboratory work, whereas agricultural universities tend to have high IGRI scores because of their large green areas and potential offsetting effects.

Table 3. Major themes from the SLR on University GHG Management

Theme	Focus areas	Share of studies
GHG Management and Carbon Accounting	Scope 1-3 inventories, EF development, quantification methods	40%
Green Campus Frameworks	UI Green Metric, eco-campus benchmarking	25%
Net Zero Strategic Planning	Institutional roadmaps, transition policies	20%
Technology and Innovation	Renewable energy, EV mobility, wastewater-to-energy	10%
Governance and Stakeholder Engagement	Policy frameworks, participatory governance	5%

	RHCI (Research–HealthcareComplexity) Reflects the intensity of research labs and hospitals (energy & carbon-intensive)	UMPI (Urban–Mobility Pressure) Captures travel pressure and density in urban settings	LGCI (Land–Green Capacity) Represents green space capacity and CO ₂ sequestration	IGRI (Infrastructure–Governance Readiness) Assesses infrastructure readiness and governance capacity
Key Variables (Indices)	- EUI (Energy Use Intensity) - LAB_SHARE (% lab/research area) - HOSP_INTENSITY (beds per area)	- DENSITY_PROXY (campus density) - MOB_CAPITA (trips per capita) - PRIVATE_SHARE (% private cars) - COMMUTE_DIST_AVG (average distance per trip) - TRANSIT_SUPPLY (public transit coverage)	- GREEN_RATIO (% green area) - AGRI_RATIO (% agricultural/research land) - CAMPUS_AREA (total land area)	- BASE_INDICES (normalized composite) - Governance proxies (Net Zero policy, MRV readiness)
Drivers	High energy demand, intensive cooling/heating, electricity per area	Private car dependency, lack of transit alternatives, Scope 3 commuting emissions	Land-use management, capacity for CO ₂ absorption via forests, trees, T-VER projects	MRV integration, carbon budgeting, roadmap readiness, stakeholder engagement
Design Factor (DF) & Strategic Variable (SV)	DF01 Energy & Carbon Management <i>(SV-DF01-02 Building Efficiency, SV-DF01-03 Smart Grid)</i> DF06 Research & Innovation <i>(SV-DF06-03 R&D in Renewables & CCUS)</i>	DF02 Sustainable Mobility <i>(SV-DF02-02 Modal Shift, SV-DF02-03 Private Car Reduction)</i> DF05 Governance <i>(SV-DF05-01 Net Zero Policy enforcement)</i>	DF04 Green Infrastructure & Ecosystem <i>(SV-DF04-01 Green Space, SV-DF04-02 Carbon Sequestration)</i> DF03 Waste & Water <i>(indirect: Smart Water, Circular Procurement)</i>	DF05 Governance & Engagement <i>(SV-DF05-02 MRV, SV-DF05-03 Stakeholder Engagement)</i> DF06 Education & Research <i>(SV-DF06-01 Sustainability Curriculum)</i>

Figure 2. Synthetic driver indices and clustering structure

3.2 Emissions baselines and university clustering

Thai universities were grouped into four clusters: (1) urban flagships with high emissions intensity, (2) regional comprehensives like KKU with moderate intensity and high sequestration, (3) smaller suburban universities with moderate profiles, and (4) agricultural universities with high sequestration potential. The indicators applied include Energy Use Intensity (kWh/m²/year), Emission Intensity per student (tCO₂e/student/year), Sequestration Index (tCO₂e/hectare/year), and Commuting Emission Share (% of total emissions). The clustering framework enables benchmarking across institutions and prioritization of interventions based on context-specific profiles, consistent with empirical approaches by Lin et al. (2024) and Helmers et al. (2021). The results are summarized in Table 4, which compares annual emissions, campus size, emission intensity, and sequestration proxies across the four clusters.

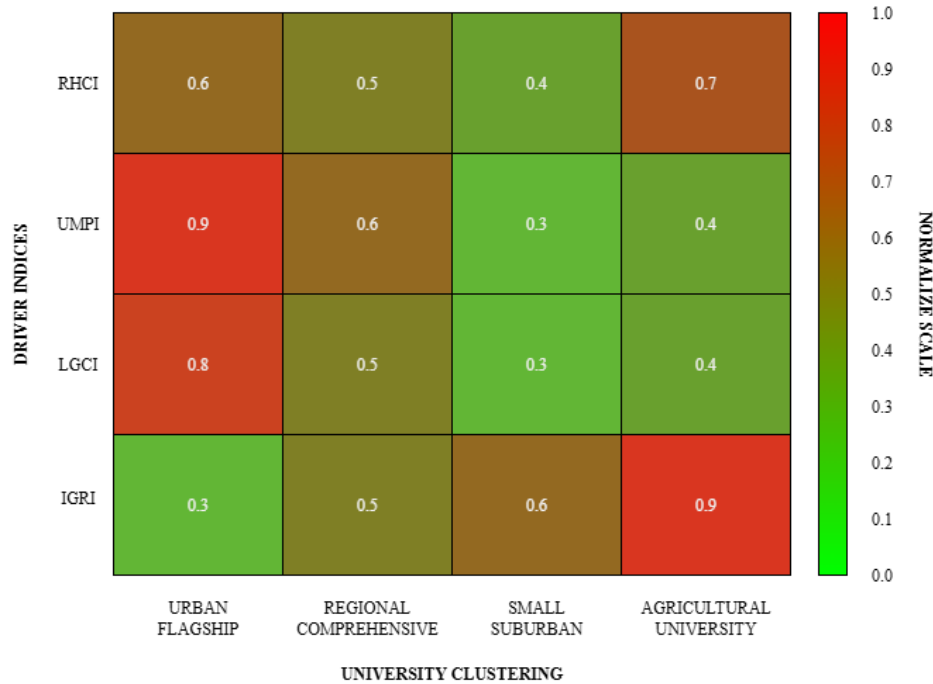
Rather than labeling clusters by institutional type, we define them by observable operational profiles. For instance, Cluster 3 represents smaller,

teaching-focused campuses with lower energy intensity and limited research/healthcare functions. Importantly, Rajabhat universities appear in multiple operational profiles; therefore, we do not treat ‘Rajabhat’ as a proxy for low emissions. Within-cluster dispersion (SD and range) is reported to reflect heterogeneity.

The heatmap analysis (Figure 3) illustrates the distribution of strengths and weaknesses across the four university clusters. These findings align with studies on land-use optimization in Chinese urban contexts, which emphasize the need to balance expansion and sustainability (Wang et al., 2022). Additionally, lessons from carbon-neutral campus building projects in Europe and the United States highlight the trade-offs between retrofitting existing facilities and designing new zero-energy buildings (Del Borghi et al., 2021). Together, these insights reinforce the practical utility of the clustering model in identifying tailored pathways for different university archetypes.

Table 4. Annual institutional emissions, campus scale, and sequestration potential

Cluster	Cluster 1: Urban flagship	Cluster 2: Regional comprehensive	Cluster 3: Urban/smaller	Cluster 4: Agricultural/green
Annual emissions (tCO ₂ e/year)	~140,000	~125,000	~40,000	~60,000
Campus size (ha)	300	880	600	1,500
Emissions intensity (tCO ₂ e/ha)	467.00	142.00	67.00	40.00
Sequestration capacity (tCO ₂ e/year)	2,500	18,000	6,000	25,000
Normalized emissions (0-100)	100	89	29	43
Normalized sequestration (0-100)	10	72	24	100


Figure 3. Heatmap-relationship of driver indices and university clustering

3.3 Design factor matrix

Six domains define the design factors: Built and Energy, Mobility, Waste, Water, Land Use, and Governance. Each domain links indicators to interventions:

- Built and Energy: retrofit index (% of buildings upgraded), renewable energy fraction (%), energy efficiency ratio (kWh/m²).
- Mobility: modal shift index (% shift from private vehicles), EV adoption rate (% of campus fleet), commuting emission per capita (kgCO₂e/person).
- Waste: recycling ratio (% of waste recycled), waste-to-energy conversion rate (%), composting efficiency.
- Water: water reuse rate (%), wastewater treatment efficiency (%).
- Land Use: green space per capita (m²/person), sequestration factor (tCO₂e/hectare).

- Governance: policy integration index (0-5 scale), MRV maturity score (1-4 levels).

This structured matrix follows models proposed by [Wang et al. \(2023\)](#) and [Aghamolaei and Fallahpour \(2023\)](#), ensuring measurable pathways for net-zero planning.

3.4 Comparative international insights

Drawing on peer-reviewed articles published between 2020 and 2025, we compare KKU's profile with international patterns. A recent global review of higher education carbon footprints ([Paredes-Canencio et al., 2024](#)) shows that Scope 3 sources (commuting, procurement, food, and waste) often dominate campus emissions, especially in developing regions with high reliance on private vehicles. This aligns with KKU's inventory, where commuting and procurement are significant contributors. Methodologically, [Helmerts et al. \(2021\)](#) emphasize the importance of transparent

system boundaries and harmonized MRV, while [Zheng et al. \(2021\)](#) demonstrate how ecological footprint-based accounting can complement traditional GHG inventories. Both approaches reinforce our call for a digital MRV backbone.

Case-based empirical studies further highlight differences. [Lin et al. \(2024\)](#) employ the emission-factor method at Zhejiang Ocean University, demonstrating how campus-specific activity data (electricity, fuels, waste) and local factors significantly impact the results. Our clustering approach follows this logic by categorizing Thai universities according to their emission intensity and sequestration capacity. [Li and Jia \(2022\)](#) examine the feasibility of achieving campus carbon neutrality, focusing on financial constraints and operational trade-offs. Our results support the need to emphasize internal pricing and investment signals alongside technical upgrades.

In terms of strategic design, [Wang et al. \(2023\)](#) propose a systematic, cross-domain framework (energy, mobility, buildings, operations) that mirrors our design factor architecture, while [Aghamolaei and Fallahpour \(2023\)](#) synthesize actionable measures (efficiency retrofits, demand management, renewables, and circularity) consistent with the interventions prioritized for KKU. [Islam et al. \(2023\)](#) position campus action plans as catalysts for city-scale transitions, which reinforces KKU's role as a regional "living lab," where EV transit, wastewater-to-biogas, and nature-based sequestration can scale beyond campus boundaries.

Taken together, the 2020-2025 literature converges on three comparative insights relevant to KKU: (i) Scope 3 management and MRV harmonization are decisive ([Helmerts et al., 2021](#); [Paredes-Canencio et al., 2024](#)), (ii) context specific factorization of activity data and localized emission factors are essential for credible baselines ([Zheng et al., 2021](#); [Lin et al., 2024](#)), and (iii) integrated, cross-domain frameworks paired with feasible financing and governance instruments are prerequisites for credible net-zero pathways ([Wang et al., 2023](#); [Li and Jia, 2022](#); [Aghamolaei and Fallahpour, 2023](#); [Islam et al., 2023](#)).

3.5 Case study: KKU

Khon Kaen University (KKU) was analyzed as a model of a campus-as-city system, reflecting the interlinked dynamics of energy, transport, waste, water, and land use. The case illustrates both the

strengths and constraints of a large Thai regional university and demonstrates how design factors and strategic variables can guide tailored net-zero planning.

To contextualize KKU's profile, we benchmark its EUI and emissions intensity against published campus inventories and the Thai sample range. We further test sensitivity to the grid emission factor and commuting assumptions to determine whether KKU's pattern is typical for regional comprehensive universities or driven by case-specific factors (e.g., hospital demand share).

KKU consumes more than 102 million kWh of electricity annually, with the hospital complex alone accounting for nearly 40% of demand. The university's Electricity Use Intensity (EUI) ranges between 250-300 kWh/m²·year, significantly above international benchmarks (150-200 kWh/m²·year), reflecting Thailand's hot climate and dependence on air conditioning.

- Scope 1 emissions: derived from LPG, refrigerants, and campus vehicles.
- Scope 2 emissions: dominated by purchased electricity, forming the largest share of the carbon footprint.
- Scope 3 emissions: commuting and procurement remain underreported, with private vehicles responsible for more than 70% of daily trips.

Using the cluster-based framework, KKU (Cluster 2: Regional Comprehensive) reported ~125,000 tCO₂e annually across its 880-ha campus. This corresponds to a moderate emissions intensity (~approximately 142 tCO₂e/ha). Importantly, with more than 60% of land designated as green or agricultural zones—including a 240-ha restored dry dipterocarp forest—KKU demonstrates one of the highest sequestration capacities (~18,000 tCO₂e/year) among Thai universities.

3.5.1 Design factors and strategic variables applied to KKU

The application of the design factor framework to Khon Kaen University (KKU) reveals how its operational profile influences the prioritization of interventions, as shown in [Figure 4](#). In the domain of Built Environment and Energy, the high Energy Use Intensity (EUI) necessitates large-scale building retrofits, photovoltaic (PV) deployment, and energy storage solutions, with monitoring based on MRV indicators expressed as kgCO₂e/m²·year. Within Mobility and Access, the predominance of private

vehicles underscores the importance of electric shuttle systems (KKU Smart Transit) and bike-sharing programs, assessed in tCO₂e/FTE·year. Waste and Circularity strategies, such as composting and wastewater-to-biogas conversion, address Scope 3 waste streams, with performance tracked via diversion rates. Similarly, Water and Blue-Green Systems integrate wastewater-to-energy projects to enhance

water efficiency while mitigating methane emissions. Land Use and Biodiversity measures emphasize the role of campus forests in carbon sequestration, expressed as tCO₂e per year. Finally, Governance and Digital Infrastructure call for integrating ISO 14064-1 standards with real-time MRV systems to ensure transparency and comparability across institutional and international benchmarks.

DF/Cluster	Large Comprehensive	Urban Specialized	Small Urban	Rural/Agricultural	Design Factor Name
DF01	1.200	0.920	0.618	0.700	Energy & Carbon Management
DF02	0.750	0.683	1.105	0.585	Sustainable Mobility
DF03	0.750	0.713	0.618	0.880	Water & Waste System
DF04	0.808	0.450	0.540	1.105	Green Infra & Ecosystem
DF05	0.750	0.840	0.920	0.690	Governance & Engagement
DF06	0.525	0.735	0.650	0.600	Education, Research & Innovation
	KKU				

Figure 4. Design factors' prioritization of interventions

3.5.2 Strategic initiatives and progress

KKU has formally committed to achieving carbon neutrality by 2040, positioning itself 25 years ahead of Thailand's national target. Strategic initiatives already implemented reflect both the university's high operational emissions and its significant potential for sequestration. These include:

1. Large-scale Renewable Deployment - 30 MW of solar farms and rooftop PV systems designed to reduce Scope 2 emissions.
2. Sustainable Mobility Transition - the launch of the KKU Smart Transit electric bus program, complemented by bicycle-sharing initiatives, directly reduces commuting-related emissions.
3. Circular Waste and Energy Projects - wastewater-to-biogas systems that capture methane and reduce Scope 1 emissions, alongside composting programs for organic waste.
4. Nature-Based Sequestration - continuous forest restoration initiatives that enhance long-term carbon sinks.

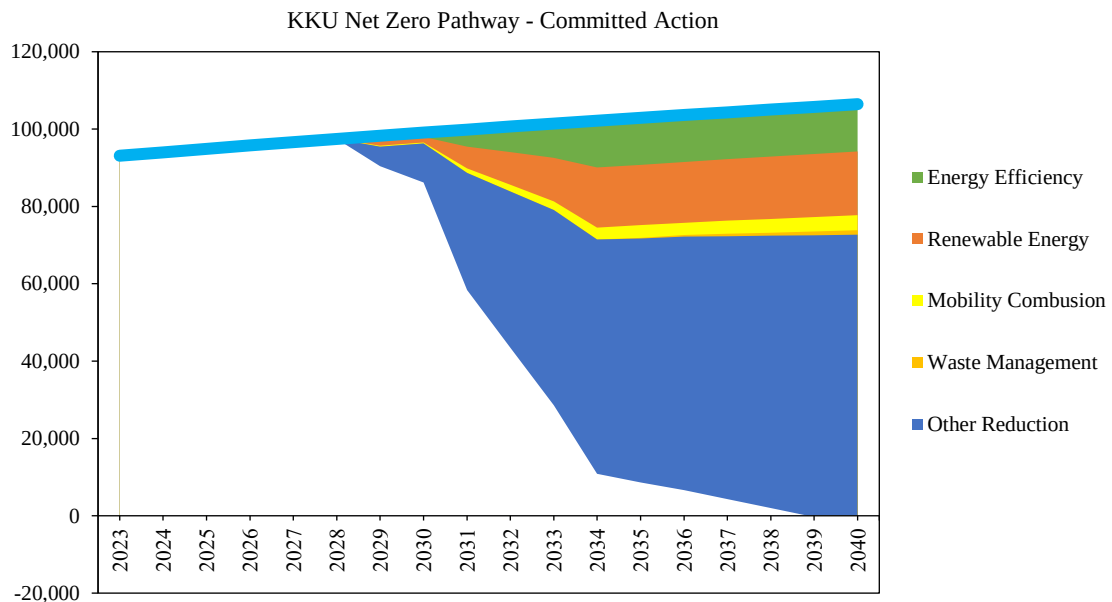
Each of these initiatives can be mapped directly to the Strategic Variables (SVs) outlined in the

Strategic Variables and GHG Reduction (Table 5), where interventions are categorized under design factors such as energy, mobility, waste, and land use. This structured alignment illustrates how institutional commitments are operationalized into measurable actions, providing both accountability and a replicable model for other universities to follow.

Importantly, these initiatives are not carried out in isolation but are integrated into a KKU Net Zero Roadmap (Figure 5), which serves as a strategic pathway linking short-term actions with long-term decarbonization goals. By incorporating the SV-based framework into the roadmap, KKU ensures that each intervention aligns with measurable GHG reduction outcomes, financial viability, and effective governance structures. This roadmap approach provides clarity on timelines, milestones, and monitoring responsibilities, while also allowing for iterative adjustments in response to emerging technologies and policy developments. As a result, it turns strategic plans into a flexible operational blueprint, strengthening KKU's position as a national and regional leader in university-driven climate action.

Table 5. Strategic variable and GHG reduction

SV Code	SV Name	DF	Scope	SV Score	GHG Reduction	Horizon
SV-DF06-03	R&D on RE & CCUS	DF06	ALL	0.010	866.23	Long
SV-DF06-02	Living Lab Campus	DF06	ALL	0.012	1,082.78	Long
SV-DF06-04	Partnership with Industry/Gov.	DF06	ALL	0.017	1,517.06	Long
SV-DF03-04	Circular Procurement	DF03	S3	0.018	373.89	Long
SV-DF05-02	MRV (ISO 14064 + TGO CFO)	DF05	ALL	0.020	1,806.03	Long
SV-DF02-02	Modal Shift (Bike/Transit)	DF02	S3	0.031	626.93	Long
SV-DF06-01	Curriculum on Sustainability	DF06	ALL	0.032	2,882.42	Long
SV-DF02-03	Policy Less Personal Car	DF02	S3	0.033	685.70	Long
SV-DF02-01	EV Campus & Charging Infra	DF02	S1	0.035	820.26	Long
SV-DF05-03	Stakeholder Engagement	DF05	ALL	0.036	3,250.85	Long
SV-DF05-01	Net Zero Policy & Roadmap	DF05	ALL	0.038	3,431.46	Long
SV-DF02-04	Business Travel Management	DF02	S3	0.039	789.33	Long
SV-DF03-01	Smart Water Management	DF03	S1	0.052	1,201.71	Long
SV-DF04-03	Biodiversity Corridors	DF04	ALL	0.054	4,931.22	Long
SV-DF05-04	Carbon Credit / T-VER	DF05	ALL	0.060	5,418.09	Long
SV-DF03-03	Zero Waste to Landfill	DF03	S3	0.067	1,377.18	Long
SV-DF01-04	Carbon Accounting & Budget	DF01	S1	0.071	1,652.39	Long
SV-DF03-02	Wastewater to Biogas	DF03	S1	0.120	2,772.53	Medium
SV-DF01-03	Smart Grid & Demand Response	DF01	S2	0.124	5,852.70	Medium
SV-DF04-04	Nature-based Solutions (NbS)	DF04	ALL	0.141	12,821.16	Medium
SV-DF04-01	Green Space Expansion	DF04	ALL	0.184	16,766.14	Medium
SV-DF01-02	Building Energy Efficiency	DF01	S2	0.191	9,029.88	Medium
SV-DF04-02	Carbon Sequestration Forestry	DF04	ALL	0.230	20,957.67	Medium
SV-DF01-01	Renewable Energy Integration	DF01	S2	0.245	11,618.60	Medium


Figure 5. KKU net zero pathway

3.5.3 Challenges and comparative insights

Despite these achievements, several limitations persist. First, the high EUI of the climate-sensitive building stock underscores the urgent need for systematic retrofitting and the implementation of

smart energy management systems. Second, Scope 3 accounting remains incomplete, particularly for commuting, procurement, and food services, thereby limiting the accuracy of KKU's carbon footprint. Third, the absence of a unified digital MRV platform

limits transparency and comparability of emissions data. Finally, a lack of financial instruments, such as internal carbon pricing or dedicated green investment funds, constrains the university's capacity to mobilize resources toward its net-zero roadmap.

3.6 Synthesized tool and application to KKU

Building on the synthesis process, the outcome was a University Net Zero Planning Tool designed to integrate data, design factors, and strategic planning. The tool consists of four modules:

(1) Inventory Module: consolidates Scope 1-3 emissions using standardized factors and institutional data.

(2) Clustering Engine: groups universities based on energy intensity, sequestration potential, and operational scale. The indicators applied include Energy Use Intensity (kWh/m²/year), Emission Intensity (tCO₂e/student/year), Sequestration Index (tCO₂e/hectare/year), and Commuting Emission Share (% of total emissions). This multidimensional clustering approach is consistent with international benchmarking methods (Helmerts et al., 2021; Lin et al., 2024; Paredes-Canencio et al., 2024).

(3) Design Factor Matrix: links each emission source to measurable indicators and potential interventions. The matrix covers six domains: Built & Energy (e.g., retrofit index, renewable fraction), Mobility (modal shift index, EV adoption rate), Waste (recycling ratio, waste-to-energy factor), Water (water reuse rate, treatment efficiency), Land Use (green space per capita, sequestration factor), and Governance (policy integration index, MRV maturity score). Similar frameworks have been outlined by Wang et al. (2023) and Aghamolaei and Fallahpour (2023).

(4) Roadmap Generator: produces scenario-based pathways aligned with national targets and institutional capacity. The generator employs back-casting principles—starting from a 2040/2050 net-zero target and mapping backward to identify milestones, technology adoption rates, and governance reforms. It incorporates sensitivity analysis for financial feasibility (Li and Jia, 2022) and city-scale transition synergies (Islam et al., 2023).

Applied to KKU, the tool quantified emissions, identified Scope 3 commuting impacts, and estimated sequestration from campus forests. It created a strategic roadmap focusing on solar expansion, EV transit, wastewater-to-biogas, and governance reforms. This roadmap was validated through expert

consultations and institutional strategy documents, ensuring both feasibility and alignment with Thailand's net-zero 2065 goals.

3.7 Strengthened discussion with recent studies

Recent works (Wang et al., 2023; Paredes-Canencio et al., 2024; Islam et al., 2023; Aghamolaei and Fallahpour, 2023; Zheng et al., 2021; Lin et al., 2024; Li and Jia, 2022) expand the understanding of carbon neutrality in universities and strengthen the framework presented here. They highlight integrated approaches, ongoing weaknesses in Scope 3 management, the need for MRV standardization, financial viability, and city-wide synergies. KKU's case aligns with these insights, confirming the global relevance of its strategies.

4. CONCLUSION

This study introduces and validates a University Net-Zero Planning Tool, a strategic framework designed to guide Thai universities toward achieving carbon neutrality by employing systematic review, clustering analysis, and the synthesis of design factors. The results confirm that Scope 3 emissions, especially those linked to commuting and procurement; are the most prominent, while sequestration potential varies across institution types. The four driver indices (RHCI, UMPI, LGCI, IGRI) offer a solid basis for classifying universities into distinct clusters, facilitating more customized decarbonization strategies.

Applied to KKU, the tool highlights both challenges and opportunities: high operational emissions but also strong sequestration potential. The framework provides a replicable model for Thai universities and contributes globally to campus-based climate governance.

The analysis reveals: (1) KKU and other flagship universities have high EUI driven by energy-intensive facilities, (2) Scope 3 sources (commuting, procurement) constitute a substantial share of campus emissions (see Figure 5), and (3) effective decarbonization requires integrated measures and an MRV system.

KKU's EUI (~270 kWh/m²) and emissions intensity are in the top quartile of the Thai sample and comparable to those of large international campuses. Sensitivity tests (varying the grid factor and commuting assumptions) show that KKU's core findings remain stable.

Policy implications are threefold. First, national and institutional climate policies must go beyond energy efficiency to include sustainable mobility, procurement, and campus-wide behavioral change. Second, developing a standardized digital MRV system is essential for transparency, comparability, and alignment with Thailand's national climate commitments. Third, tailored incentives and support mechanisms are necessary, recognizing that urban flagships, regional comprehensives, suburban universities, and agricultural campuses each face distinct carbon challenges and opportunities.

In conclusion, universities can serve as 'living laboratories' for low-carbon transitions (Evans et al., 2015; Yusoff et al., 2021), and the proposed framework offers policymakers a replicable tool to accelerate progress toward Thailand's 2050 carbon neutrality and 2065 net-zero targets. The framework is transferable to other developing-country contexts if three conditions are addressed: (i) a minimum viable dataset (Scope 1-2 plus core activity indicators), (ii) a staged plan to expand Scope 3 categories as data capacity improves, and (iii) a governance entity responsible for MRV integration and target accountability. We therefore propose a four-level adoption pathway, allowing institutions with limited data to start with robust Scope 1-2 benchmarking before progressing to full Scope 1-3 MRV and verification.

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AUTHOR CONTRIBUTIONS

Conceptualization, W.P.; Methodology, W.P.; Tool synthesis, W.P.; Data curation, W.P.; Formal analysis, W.P.; Validation, W.P. and C.T.; Writing-original draft, W.P.; Writing-review and editing, C.T.; Visualization (clustering, design factors, roadmap tool), W.P.; Supervision and policy guidance, C.T.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no competing interests.

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The White Sands of Tutong - A High Quality Sand Suitable for Photovoltaic Applications

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ABSTRACT

The renowned White Sands of Tutong in Brunei Darussalam, situated on the island of Borneo, have long been recognized as a potential source of glass-grade sand. As Brunei Darussalam seeks to diversify its economy, these sand deposits are gaining attention as a valuable mineral resource for sustainable development. Lithological investigations showed that the deposit is geologically more heterogeneous than anticipated, with the groundwater table close to the surface and the presence of red-brown sand indicating higher iron concentrations in current or former water-table fluctuation zones. This study investigated the chemical properties of the sand via ICP-OES, and XRF, which confirmed the high purity of the silica sand with low concentrations of iron. The glass produced from the raw sand exhibited a solar transmittance of 90.2%, making it suitable for photovoltaic applications. The sand should be shielded from any further development, like housing development and any development should carefully weigh the economic versus the ecological value of the sand as it also supports a rare tropical heath ecosystem.

HIGHLIGHTS

- Glass from the White Sands shows high solar transmittance for photovoltaic use.
- The deposit is more geologically heterogeneous than previously understood.
- Development must balance economic and ecological value and protect the deposit.

1. INTRODUCTION

Since the dawn of time, humans have used sand for shelter and development purposes. Sand is formed through chemical weathering and erosive processes over millions of years. Quartz sands are suitable for a wide range of industrial applications (Harben, 2002; Platias et al., 2014; Pan et al., 2022). In high-technology industries, quartz is a critical raw material used in photovoltaic cells, silicon wafers, fiber optics, and other advanced components. In particular, high-purity silica sand is essential for producing silicon, which forms the foundation of solar panels and semiconductor devices. The increasing demand for

photovoltaic and semiconductor technologies has led to a growing dependence on high-purity quartz sand as a critical raw material.

For solar applications, silica sand must meet stringent chemical and mineralogical requirements. Iron (<0.02 wt% Fe₂O₃), titanium (0.03 wt % TiO₂) and chromium (0.0005 wt% Cr) must be present only in trace amounts, as these impurities can reduce the performance and efficiency of photovoltaic materials (Vogt et al., 2016; Treviño Rodríguez et al., 2023). A consistent grain size, ranging between 0.1 to 0.6 mm (Schweiger et al., 2010; Elsner, 2016), is also necessary for industrial processing. For electronics,

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including solar cells, silica sand must exhibit extremely high quartz purity (>99.6% SiO₂) and minimal impurities to ensure reliable performance.

Solar photovoltaics are experiencing rapid growth, with China leading in installed capacity, followed by the European Union, the United States and India (Chowdhury et al., 2025). While some countries can meet their silica sand needs through domestic resources, others rely on imports (Burkowicz et al., 2020). Growing global demand, particularly for renewable energy infrastructure, has intensified pressure on existing sand sources. In many regions, overexploitation of sand has led to ecosystem degradation, biodiversity loss, and shoreline erosion, with negative consequences for human and environmental health (Bendixen et al., 2021). River sand mining is highly damaging, as it disrupts drainage networks and causes lasting ecological harm (Rentier and Cammeraat, 2022). A recent study in Brunei found that dredging and quarrying near the Brunei River had significantly increased turbidity (Onifade et al., 2023), underscoring the importance of baseline assessments for evaluating environmental impact (Oluwaniyi and Asiwaju-Bello, 2020).

Brunei Darussalam experienced substantial shoreline erosion and flood risk due to coastal sand mining in the 1950s (Chua et al., 1987; Yong, 2010; Latif and Yong, 2021), which led to the cessation of such practices. However, recent highway construction has involved sand abstraction beneath coastal peatlands, leading to drainage impacts on tropical peatlands (Suhip et al., 2020). Globally, sand is being extracted far more rapidly than it is naturally replenished. This is especially true in high-income countries, which consume ten times more raw materials than low-income ones (Schandl et al., 2018). Between 2020 and 2060, global demand for construction-grade sand is projected to rise by 45%, emphasizing the urgency for sustainable extraction practices (Zhong et al., 2022).

Sand and gravel now represent the largest share of solid material use—surpassing fossil fuels and biomass—and have experienced the fastest growth in demand (Torres et al., 2017; Krausmann et al., 2009). Unfortunately, Southeast Asia has become a global hotspot for both legal and illegal sand extraction (Park, 2024; Yuen et al., 2024).

Brunei Darussalam is actively seeking to diversify its economy beyond fossil fuels; priority sectors include high-tech industries such as semiconductors, fiber optics, advanced manufacturing

and high-tech agriculture have been identified for development (Radzuan et al., 2022). These high-tech industries rely heavily on secure access to strategic raw materials, including high-purity quartz. To support this national vision, Brunei is pursuing sustainable mining strategies and formulating green operational guidelines aimed at ensuring long-term resource availability and environmental stewardship.

The current work builds upon an earlier investigation (Gödeke et al., 2025) which examined the glass-making potential of the White Sands of Tutong and concluded that their high silica content compares favorably with other international silica sand deposits (Boussaa Anas, 2020). Expanding on these findings, the present study focuses on assessing the optical properties of glass derived from the sand, particularly for solar applications. Given the absence of updated geological data—most of which dates back to the 1950s and 1980s—this research also aims to expand the current knowledge on Brunei's White Sands of Tutong; by undertaking detailed lithological investigations through the excavation of sacrificial boreholes using a hand auger. Additional modern analytical methods were applied to assess the deposit's potential for high-tech and photovoltaic applications.

2. METHODOLOGY

2.1 Data visualization and cross-section construction

ArcGIS Pro 3.1.0 was used to generate an overview map of the study site (Figure 1), while Strater (Golden Software, Version 5.7) was used to construct the geological cross-section profile based on borehole data. The Strater software allows for the correlation of matching stratigraphic units between boreholes based on depth and contact points; if a unit was present in one borehole but was absent in the adjacent one, it was assumed to pinch out, forming a wedge-shaped polygon in the profile.

2.2 Field sampling

Lithological investigations were conducted using a bayonet hand auger (Edelman type for sandy soil, Royal Eijkelkamp). Sacrificial boreholes for lithological investigations were spaced around 500 m to 2 km apart depending on site accessibility, and were fully backfilled after sampling. Coring was limited to a maximum depth of 3 m below the surface due to the increasing difficulty of hand augering, particularly when the groundwater table was encountered. For geochemical analysis, quartz sand samples were

collected near borehole 5 using a small shovel and stored in a sampling bag before being transferred to the laboratory.

2.3 Geochemical analysis

Trace element concentrations were measured at the MASA Institute (Göttingen, Germany) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; iCAP Pro XP, Thermo Scientific) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS; iCAP TQe, Thermo Scientific). This means that after complete digestion using HF-HNO₃-HCl, the samples were diluted 1:1,000 with 2% HNO₃ so that they could be measured by the instruments. The dual approach of using ICP-OES and ICP-MS was chosen for quality control and analytical reasons. For example, sulfur was analyzed using ICP-OES due to spectral interferences and its ionization behavior in ICP-MS. Prior to glass preparation, the sand was dry sieved, and the grain-size fraction between 125 µm (ASTM No. 120) and 355 µm (ASTM No. 45) was retained. This fraction was washed 4 times with demineralized water, with excess water decanted after each wash, and subsequently dried in a drying cabinet at 90°C. A typical soda-lime float glass composition (74 mol% SiO₂, 16 mol% Na₂O, 10 mol% CaO) was chosen, as soda-lime float glass is widely used in solar panel manufacturing due to its low cost, mechanical strength, and ease of mass production. For the glass batch, 88.8 g of SiO₂, 34 g of Na₂CO₃, and 20 g of CaCO₃ were used, totaling 142.8 g based on the molar compositions. The Na₂CO₃, with a purity of greater than 99.9%, was sourced from Merck and the CaCO₃, with a purity of 99.95%, from Strem Chemicals.

2.4 Glass synthesis and optical characterization

The glass melting and subsequent analysis were conducted at the Institute of Non-Metallic Materials, Clausthal University of Technology, Germany. The batch mixture was heated in a platinum crucible up to 1,550°C in the oven over a period of 2 h and kept at this temperature for 1 h for homogenization. The glass melt was then cast in a graphite mold with the dimensions of 40×40×20 mm and transferred into a cooling furnace for relaxation at 550°C for 4 h, followed by cooling down to room temperature within 10 h. From the glass block, a slice approximately 20×20 mm, with a thickness of 3 mm, was cut and polished up to grit 4,000 to obtain a very smooth polished surface suitable for optical analysis.

The transmission spectrum of the prepared glass slice was measured using a PerkinElmer Lambda 950 UV-Vis-NIR spectrophotometer equipped with an integrating sphere (150 mm) and solar transmittance was calculated according to DIN EN 410. In this norm the average transmittance in the wavelength ranges from λ=300 to 2,500 nm is weighted by the air mass 1.5 radiation and calculated as

$$\tau = \frac{\int_{300 \text{ nm}}^{2,500 \text{ nm}} \tau_{\lambda} \times S_{\lambda} \times d\lambda}{\int_{300 \text{ nm}}^{2,500 \text{ nm}} S_{\lambda} \times d\lambda} \quad (1)$$

where; T_{λ} is the wavelength-dependent transmittance of the coated glass and S_{λ} the solar radiation function for air mass 1.5 (ASTM G173-03). The glass composition was analysed using an energy dispersive X-ray fluorescence spectrometer (XRF), Model EDX-700P, Shimadzu.

Primitive mantle-normalized multi-element spider diagrams were generated using normalization values from McDonough and Sun (1995), enabling assessment of trace element enrichment and depletion patterns relative to bulk silicate Earth composition. In addition, a chondrite normalized REE-pattern graph was generated.

2.5 Study site

Located near Tutong town in Brunei Darussalam, approximately 60 km from the capital Bandar Seri Begawan, the White Sands of Tutong represent a significant silica sand deposit (Figure 1). First documented by Wilford (1961), the deposit is believed to be the remnant of an ancient beach dune system formed during a marine transgression. The silica sand deposit stretches approximately 11 km in length and 2 km in width and is intersected by the Seria-Tutong highway: with the sands forming terraces rising to about 15 meters above sea level and overlying flat Quaternary clay deposits (Sandal, 1996). A recent study by Gödeke et al. (2025) redefined the extent of the deposit, highlighting notable discrepancies between the original boundary proposed by Wilford and the updated delineation, likely due to both improved geological surveying techniques and natural changes in surface features over time.

Previous observations identified two primary sand layers: an upper white fine sand ranging from 0.6 to 4.6 meters thick, and a lower humus-stained fine sand. The estimated volume of the white sand layer is approximately 15 million m³ (Sandal, 1996). Notably, the site also supports a rare tropical heath forest

ecosystem (Din et al., 2015), underscoring the need for any future development to balance ecological

preservation with the potential for mineral exploitation (UNEP, 2019).



Figure 1. Study site with extent of silica sand and location of hand-augered boreholes, Tutong, Brunei Darussalam

3. RESULTS AND DISCUSSION

This section presents the findings from the lithological investigation, geochemical analysis of the silica sand, and optical characterization of the glass product derived from the White Sands of Tutong.

3.1 Study area and geological setting

The lithological profile obtained from the hand-augered boreholes is shown in Figure 2. The results of the lithological investigations clearly show that the sand deposit is not composed solely of white fine sand, which had previously been characterized as a moderately well sorted fine sand, with symmetrical graphic skewness and mesokurtic graphic kurtosis (Gödeke et al., 2025). The present investigation reveals a more heterogeneous stratigraphy, with the white sand facies forming a dominant and continuous upper layer across most boreholes, except where it is truncated by overlying blackish, grey, or red-brown sands.

In particular, BH1 to BH3 show interruptions of the white sand layer by overlying black and red-brown sands, indicating facies variation, possible surface reworking, or post-depositional alteration in the northwestern part of the deposit. Black sand,

encountered in these boreholes, is rich in organic matter and often lies above either red-brown or white sand, suggesting dynamic depositional processes or subsequent transformation under reducing conditions. The red-brown sands were already observed by Wilford (Wilford, 1961) and appear discontinuous across these locations. They typically occur near the top of the groundwater table, likely representing oxidation-reduction (redox) interfaces associated with historic groundwater fluctuations. These zones are typically visibly enriched in iron oxides, most likely in the form of hematite (Fe_2O_3), formed under alternating oxic and anoxic conditions (Usman et al., 2021). Grey sand, on the other hand, is a less dominant facies and appears mainly in BH2 and BH4, which may represent localized transitional zones within the depositional environment. The grey coloration of the sand is likely attributed to the presence of iron-bearing minerals, minor clay or organic coatings on quartz grains or some heavy mineral fractions.

Figure 3 confirms the shallow position of the groundwater table at BH3. Although the figure does not depict water chemistry, previous hydrogeological studies in Brunei have shown that such shallow aquifers commonly contain elevated dissolved iron

(Azffri et al., 2023; Azhar et al., 2019). This iron-enrichment, if remobilized into the sand matrix, could pose a contamination risk that may affect optical

clarity and purity which are key parameters in glass used for photovoltaic applications.

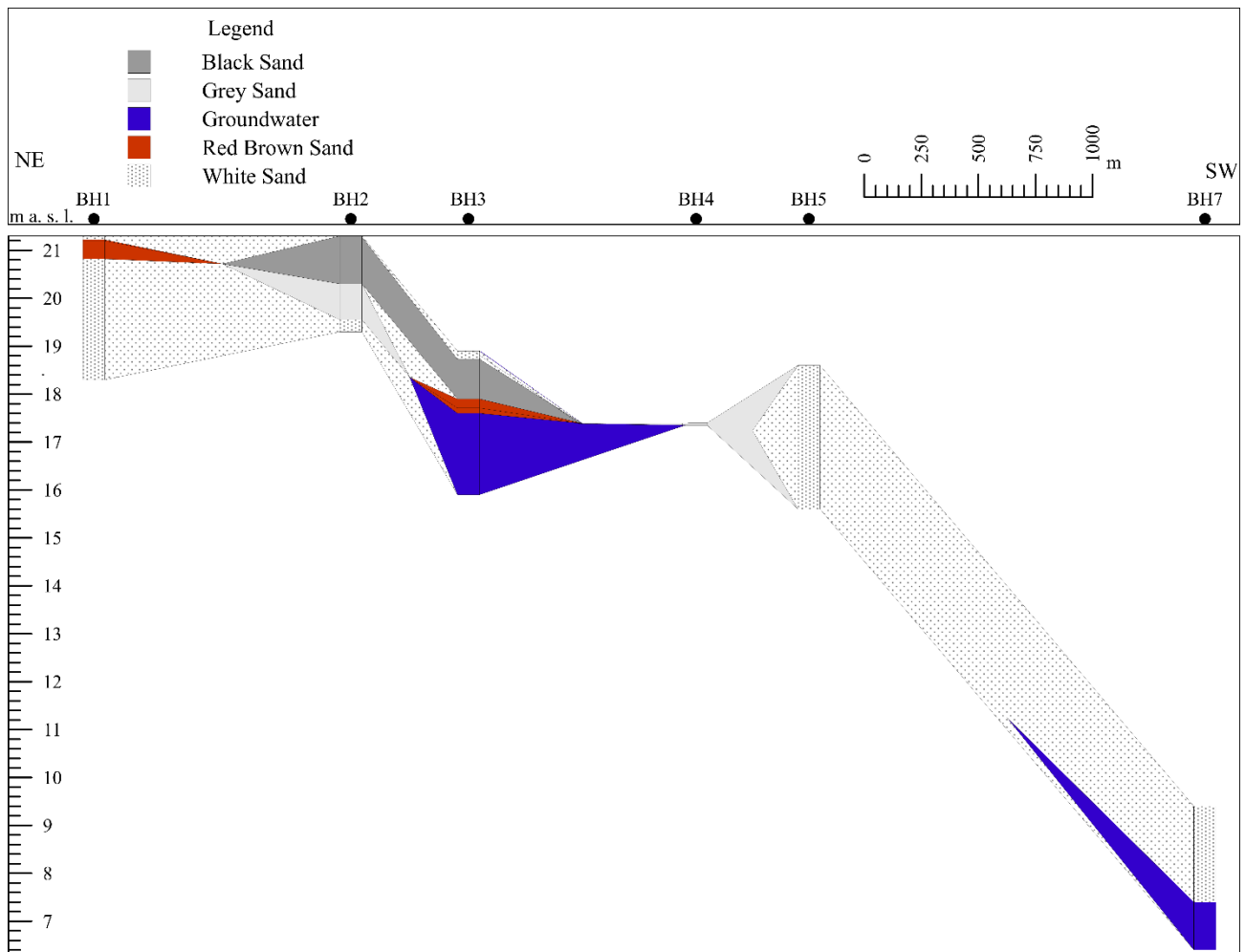


Figure 2. Geological cross section along the hand-augered boreholes

A spatial trend is also evident: towards the southeast (BH5-BH7), the deposit becomes more uniform, consisting almost entirely of clean white sand with minimal organic or iron-bearing material. These southeastern zones may be more suitable for industrial extraction, particularly where high silica purity is required for industrial or photovoltaic applications, where even trace impurities such as Fe, Ti, or organics can reduce solar transmittance and energy conversion efficiency.

To better understand the internal architecture and hydraulic behavior of the deposit, further hydrogeological or tracer-based investigations are recommended. Evaluating the connectivity between different facies and the role of low-permeability layers

could help predict impurity and fines migration pathways, groundwater influence, and long-term quality consistency which are all critical for maintaining sand standards suitable for photovoltaic (PV)-grade glass (Gödeke et al., 2008; Gharbi et al., 2014; Sazali et al., 2018).

Overall, the lithological investigations confirm that the White Sands of Tutong exhibit greater heterogeneity than previously reported, with implications for both resource management and ecological preservation. Identifying zones of low impurity concentration, minimal redox alteration, and limited organic content will be key to maximizing the potential of the deposit as a strategic raw material for solar energy applications.



Figure 3. (a) Coring with auger (b) Surrounding environment at site 1 (c) Reflection of the groundwater table at borehole 3 (BH3)

3.2 Geochemical characterization and trace element analysis

Geochemical analysis via ICP-OES and ICP-MS revealed that the white sand fraction appears to show a slight enrichment in titanium, with a concentration of 441 $\mu\text{g/g}$. The iron concentration was measured to be 200 $\mu\text{g/g}$. This is hardly surprising, given that titanium-bearing minerals such as rutile and

ilmenite are highly resistant to chemical weathering (Goss and Oliver, 2023). However, the Spider diagram does not show an enrichment in Titanium (Figure 4). The graph shows a major negative Strontium anomaly, in line with intense chemical weathering and plagioclase removal. The overall flat REE pattern suggests intense leaching and silica rich material.

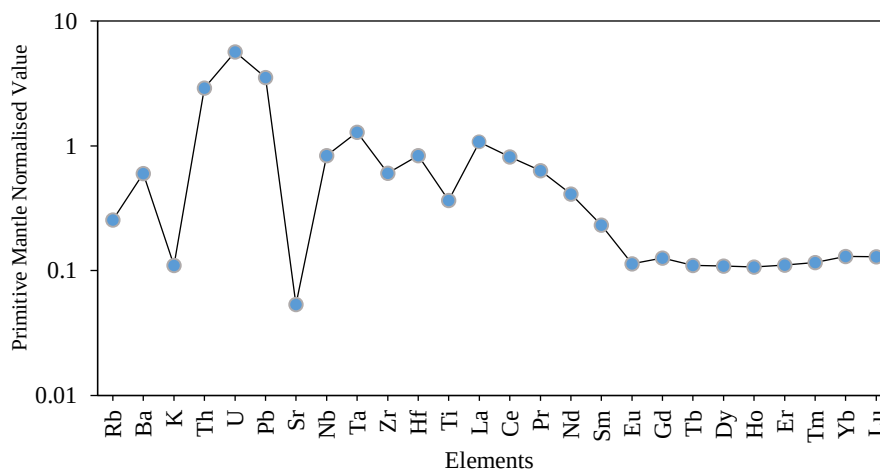


Figure 4. Spider Diagram, primitive mantle normalized, of silica sand sample

The rare earth element (REE) pattern graph, as shown in Figure 5, suggests a felsic provenance for the sand. A calculated La/Th ratio of 3.02 is consistent with derivation from the upper continental crust, which is characteristically silica rich. The cerium

anomaly, close to 1, indicates no significant redox-related fractionation, while a negative europium anomaly implies feldspar depletion, typically resulting from prolonged chemical weathering.

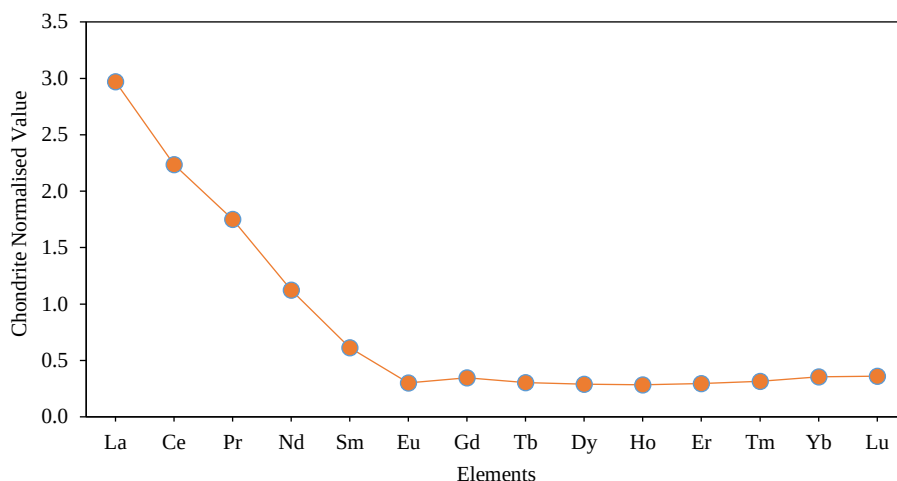


Figure 5. REE-pattern graph of silica sand sample, chondrite normalised

These signatures collectively reflect a chemically mature and recycled sediment, supporting the interpretation that the deposit originated from felsic rocks and was modified by prolonged weathering and reworking in a coastal dune environment (Götze and Lewis, 1994).

In addition, the REE pattern exhibits light REE (LREE) enrichment relative to heavy REEs (HREEs), consistent with felsic source rocks and further supporting an upper crustal origin. The lack of enrichment in transitional metals such as Cr, Co, and Sc suggests an absence of significant mafic or volcanic input. Moreover, the relatively flat HREE distribution and absence of anomalous spikes indicate minimal hydrothermal overprinting or heavy mineral contamination. Together, these features reinforce the interpretation of the White Sands of Tutong as a geochemically mature deposit with limited post-depositional alteration, underscoring its potential as a

high-quality raw material for photovoltaic glass production.

Based on the favorable geochemical characteristics of the white sand, particularly its high silica content and low levels of impurities, the material was subsequently used to prepare glass melts for further evaluation.

3.3 Optical properties of the synthesized glass

The glass transition temperature was measured to be 549.5°C, which is within the expected range for soda-lime glass and indicates good thermal stability; this is a key requirement for photovoltaic application, which must withstand prolonged outdoor exposure and thermal cycling. The composition of the two prepared glass melts, measured by XRF, is summarized in Table 1, which confirms that both batches closely matched the target composition (74% SiO₂, 16% Na₂O, and 10% CaO). Transmittance measurements were made for Glass 1.

Table 1. Composition of two glass melts (Glass 1 and Glass 2) with Brunei silica sand

Parameter	Glass 1		Glass 2	
	Mass%	mol%	Mass%	mol%
SiO ₂	75.38	75.7	75.37	75.4
Na ₂ O	15.72	15.3	15.86	15.4
CaO	8.46	9.1	8.55	9.2
Fe ₂ O ₃	0.131	0.049	N/A	N/A
Total	99.69		99.78	

The close agreement with standard soda-lime float glass compositions, commonly used in solar panels (Pilkington, 2025), demonstrates the chemical compatibility of the Tutong sand for photovoltaic glass production. The high SiO_2 content, sourced directly from the sand, is essential for achieving the optical transparency and thermal resistance required in PV applications. Moreover, the appropriate balance of Na_2O and CaO contributes to the glass's workability, durability, and mechanical strength, all of which are vital for long-term outdoor performance.

However, minor bubbles and streaks were observed in the resulting glass samples (Figure 6), which may have resulted from incomplete melt refinement or temperature gradients during the melting and cooling phases. Despite their presence, these bubbles did not significantly affect the optical performance of the glass, as confirmed by subsequent transmittance measurements. Nevertheless, future melt refinement, such as the use of fining agents or optimized annealing protocols, could further reduce bubble content and enhance the optical quality, thereby improving its suitability for high-performance photovoltaic applications.



Figure 6. Molten glass sample (40×40×20 mm) from Brunei silica sand

The solar transmittance of the polished 3 mm glass slice was measured to be 90.2%, confirming its suitability for photovoltaic applications (Lim et al., 2021). As shown in Figure 7, the glass performs better than conventional float glass (solar transmission 87.2%) and is comparable to borosilicate glass (solar transmission 92.2%). Importantly, the glass maintains

high transmissivity even at longer wavelengths, unlike float glass, which exhibits a notable decline. In comparison, commercial solar glass, typically a low-iron soda-lime-silicate glass of similar thickness, has a reported solar transmittance of approximately 90.3% (Pilkington, 2025), placing the glass well within the expected range for photovoltaic-grade materials.

The slightly lower solar transmittance than that of the borosilicate glass may be attributed to its elevated titanium concentration; titanium, particularly in the form of TiO_2 , can reduce optical clarity at certain wavelengths (Albarzan et al., 2021). Despite the slightly lower transmittance compared to borosilicate glass, the glass presents several practical advantages for photovoltaic applications. Most notably, the glass is expected to be more cost-effective to produce, due to lower melting temperatures and reduced energy requirements. It also offers better thermal compatibility with other PV module components, which is essential for minimizing stress and degradation under fluctuating outdoor temperatures. In addition, its ease of fabrication, including cutting, polishing, and tempering, makes it highly suitable for industrial-scale production. Importantly, the glass closely aligns with standard float glass compositions (Pilkington, 2025), ensuring drop-in compatibility with existing PV manufacturing infrastructure. Finally, the use of locally sourced silica sand from Tutong enhances supply chain sustainability and supports national resource utilization. Together, these factors make the glass suitable for cost-effective photovoltaic applications. Anti-reflective coatings applied on the glass could further increase the solar transmittance. A study by Hensch and Deubener (2012) found that applying a pure porous silica coating increased the solar transmittance of a silica glass by 4.1%.

3.4 Implications for Brunei's silica sand development

The present investigation confirms that the White Sands of Tutong exhibit high silica purity and favorable optical properties for photovoltaic applications. These results are consistent with earlier exploration studies that highlighted the national significance of this deposit. Initial surveys in the commissioned by the Brunei Economic Development Board (BEDB) in 2012 delineated an estimated 46 million metric tonnes of silica sand in Tutong District, covering approximately 2,000 acres (BEDB, 2012). Within this reserve, a particularly high-grade zone was

identified with approximately 14 million tonnes of sand exhibiting exceptional purity levels of 99.5-99.9% SiO₂ (BEDB, 2012). Such figures underscore the strategic importance of the deposit as one of the few documented silica resources in Brunei with characteristics that approach international benchmarks for advanced industrial applications.

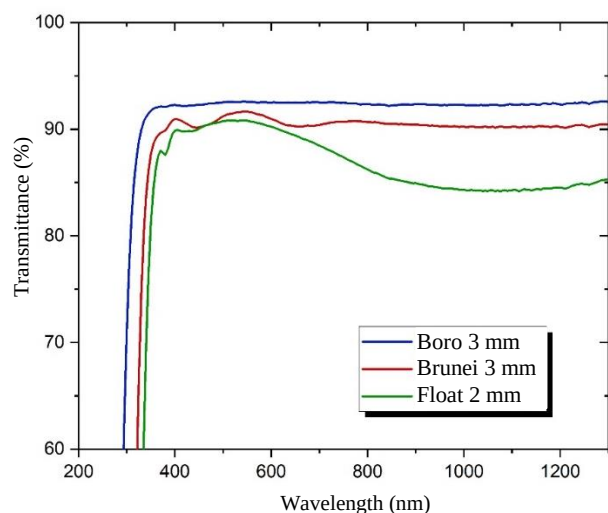


Figure 7. Transmittance of 3 mm thick Brunei glass sample compared with 2 mm standard float and 3 mm borosilicate glass

A spectrum of industrial uses emerges when considering both historical reserve estimates and the current laboratory-based analyses. Beyond photovoltaic glass, which this study has demonstrated to be technically feasible, Brunei's silica sand could serve multiple industries. These include glass manufacturing (from tableware and container glass to optical-grade products) (BS2975, 1988), silicon production for semiconductors and solar cells, fused silica for specialty optics, refractories and abrasives, foundry moulds, sodium silicate, and insulating fibres.

To realize this potential, attention must be given to beneficiation and processing requirements. The sand from Tutong, while already of high quality, will require classification, scrubbing, washing, flotation, and drying to consistently meet the stringent specifications for high-purity glass and photovoltaic silicon (>99.6-99.9% SiO₂, <0.02% Fe₂O₃) (Elsner, 2016; Vogt et al., 2016).

Looking forward, strategic partnerships with foreign investors or technology providers could facilitate the establishment of domestic glass and silicon processing plants, creating skilled employment opportunities and enabling technology transfer (Chowdhury et al., 2025). On the other hand, the ecological sensitivity of the White Sands of Tutong,

home to a rare heath forest ecosystem (Din et al., 2015) and underlain by shallow aquifers (Azffri et al., 2022; Junaidi et al., 2025), requires rigorous environmental management. Any mining operation would necessitate comprehensive environmental impact assessments, water management strategies, and alignment with Brunei's National Climate Change Policy to ensure that development remains consistent with sustainability principles. Any potential resource extraction should allow for remediation work covering the same size as the affected area to protect the natural environment.

4. CONCLUSION

High-purity silica sand is an essential raw material for advanced technologies, particularly in the photovoltaic (PV), semiconductor, and optical industries. In the context of Brunei's national agenda to diversify its economy beyond fossil fuels, the availability of local strategic minerals such as quartz becomes increasingly important. The White Sands of Tutong, historically recognized for their visual distinctiveness, are among the few known silica deposits within the country, but yet, until now, limited modern assessments have been conducted to evaluate their industrial suitability and environmental constraints.

This study combined lithological investigations, via hand-augered boreholes, with laboratory-based geochemical and optical analyses to assess the composition and potential uses of the deposit. Subsurface profiling revealed that the sand body is more geologically complex than previously reported, with localized occurrences of red-brown and black sands that interrupt the continuity of the white sand layer. These facies appear associated with varying redox conditions, groundwater dynamics, and possible post-depositional alteration. The presence of a shallow water table and a rare tropical heath forest further emphasize the ecological sensitivity of the site. Geochemical analysis confirmed the sand's high silica content, with a slight enrichment in titanium attributed to the presence of resistant minerals such as rutile and ilmenite. Rare earth element (REE) ratios indicated a felsic provenance and advanced chemical maturity. Glass produced from the sand achieved a solar transmittance of 90.2%, outperforming conventional float glass and approaching the levels seen in borosilicate and commercial solar glass. These results show that the sand is suitable for PV applications.

The measured transmittance and chemical composition indicate that the Tutong sand meets key requirements for photovoltaic glass production. However, the ecological and hydrological sensitivities identified during the investigation warrant serious consideration. Any future development of this resource must balance economic potential with long-term environmental stewardship.

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AUTHOR CONTRIBUTIONS

Conceptualization, SG, Methodology, SG, AA, AS, GH, NS, JD, EA Field Work NS, Formal Analysis: GH, JD, JW, NS, SG, AA, EA Project Supervision, SG, AA, EA, AS, Writing First Draft: SG, Writing Review and Editing, SG, AA, AS, JW, GH, NS, EA, JD.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no competing interests.

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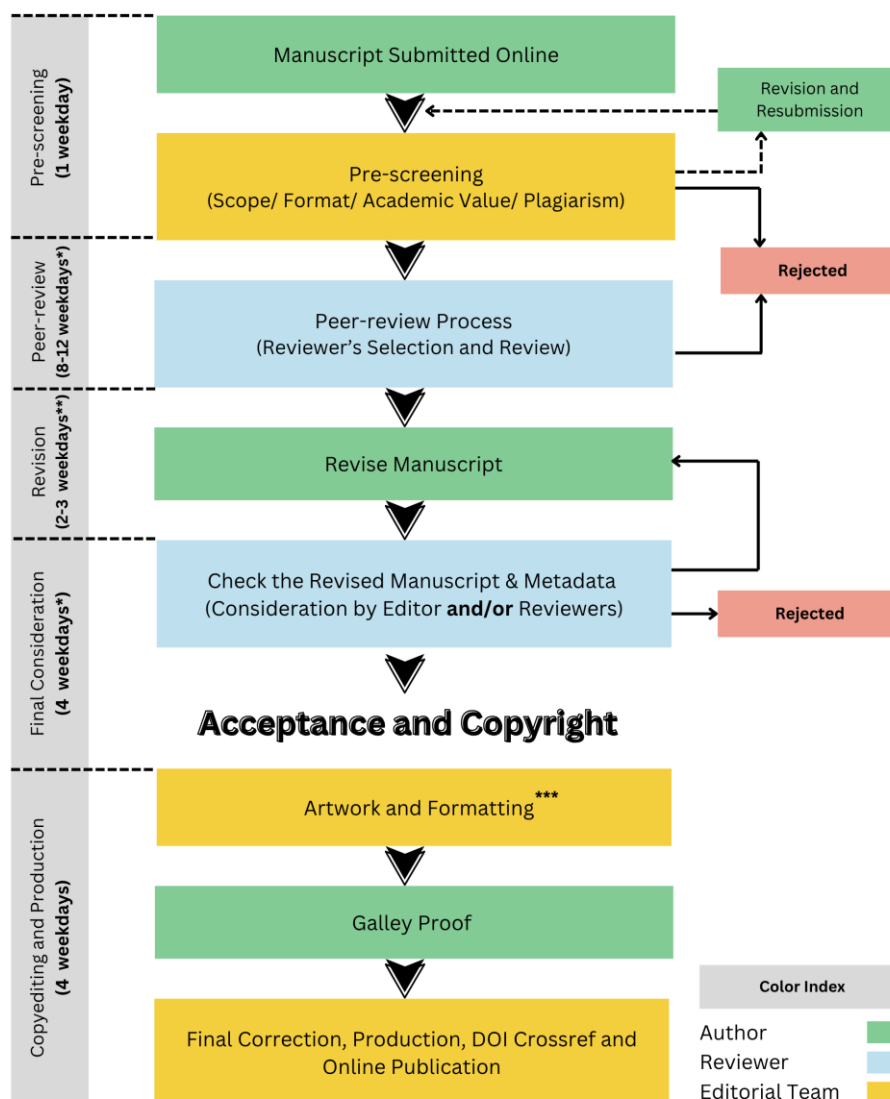
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Intergovernmental Panel on Climate Change (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories: Volume 1-5. Hayama, Japan: Institute for Global Environmental Strategies; 2006.

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