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Vol. 35 (3) 2026 Issue 113

Contents

Wydawnictwo SGGW, Warsaw 2026

Wydawnictwo SGGW   wydawnictwosggw

Editorial work – Anna Dołomisiewicz, Tomasz Ruchniewicz

ISSN 1732-9353 (suspended)   eISSN 2543-7496

Scientific Review Engineering and Environmental Sciences (2026), 35 (3), 241–260

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Multi-response optimization of red mud and sand proportions in paving block production via response surface methodology (RSM)

Keywords: response surface methodology, red mud, paving block, multi-response optimization, sustainable construction materials

Introduction

Paving blocks are widely used as interlocking concrete elements for roadways, parking areas, pedestrian paths, and landscape applications due to their ease of installation, durability, and aesthetic flexibility. According to the Indonesian National Standard SNI 03-0691 (Badan Standardisasi Nasional [BSN], 1996), paving blocks are manufactured from a mixture of portland composite cement or other hydraulic binders, water, aggregates, and optional additives that do not adversely affect the quality of concrete blocks. Based on their compressive strength, paving blocks are classified into four quality grades: Class A for roads, Class B for parking areas, Class C for pedestrian pathways, and Class D for parks and other light-use applications (Io et al., 2024).

In recent years, the rapid increase in the prices of construction materials, particularly cement and natural sand, has significantly affected paving block production costs, leading to reduced profit margins for manufacturers. In cities such as Pontianak, the market price of paving blocks ranges from 90,000 IDR·m^{-2} to 120,000 IDR·m^{-2}, with material costs being the dominant contributing factor. This economic challenge has encouraged the exploration of alternative and low-cost materials that are locally available and environmentally sustainable (Arya & Sahu, 2024).

Red mud, a by-product generated from alumina extraction through the Bayer process, has emerged as a promising alternative material in construction applications. On average, 0.3–0.5 tons of red mud are produced per ton of alumina, depending on the bauxite grade (Power et al., 2011). Liu et al. (2011), and Liu and Li (2015) reported that red mud is characterized by high alkalinity and the presence of trace radioactive elements and heavy metals, which may pose environmental hazards if not properly managed or disposed of. Consequently, the utilization of red mud in construction materials offers a dual benefit: reducing environmental pollution while lowering the consumption of conventional cement.

Red mud has the potential to be utilized in cement-based materials due to its high alumina, iron oxide, and silica contents, as well as its alkalinity and fine particle characteristics. These properties may contribute to its interaction with cementitious systems and influence strength development in cement-based materials (Sutar et al., 2014). According to numerous studies, compressive strength can be enhanced or maintained by partial replacement of cement with red mud, but only within a specific range of replacement. For instance, a red mud replacement of approximately 10–20% has been found to provide comparable or superior strength. In contrast, excessive replacement may reduce strength due to dilution effects and changes in binder reactivity. The chemical and mineralogical composition of red mud varies with bauxite source, geographical origin, and alumina-refining process, which is why these findings are not always consistent. Mix-specific evaluation is required due to the impact of this variability on its reactivity, alkalinity, and interaction with cement hydration products.

Studies focusing on paving blocks are comparatively scarce, despite previous research investigating red clay in cement mortar, concrete, and geopolymer systems (You et al., 2018). Existing paver-block studies have typically assessed specific red mud percentages or employed red mud primarily as a geopolymer precursor. However, they have not comprehensively optimized red mud–cement paving block mixtures by systematically linking replacement levels, mix proportions, and compressive strength. Thus, the present investigation's novelty lies in its systematic assessment and optimization of red mud as a partial cement substitute in paving blocks. The primary objective is to determine the optimal replacement level that enhances compressive strength while simultaneously addressing the variability in red mud properties. Compared with previous research that focused on conventional concrete, mortar, or geopolymer applications, this study provides new experimental evidence for the use of locally sourced red mud in the production of paving blocks. It establishes a more practical mix-design foundation for sustainable pavement materials.

In contrast to previous research that primarily examined red mud in conventional concrete or mortar systems, the current study focuses on the production of paving blocks. It systematically evaluates the optimal red mud replacement level with respect to compressive strength. This research addresses a current lacuna in the literature by introducing a mix-proportion optimization framework for red mud-based paving blocks that utilizes locally available red mud with unique chemical properties.

Therefore, this study proposes a multi-response optimization approach using response surface methodology (RSM) (Regulacion & Oreta, 2013; Abouhelal et al., 2023; Khan et al., 2025) to simultaneously evaluate and optimize the proportions of red mud and sand in paving block production. By considering multiple performance indicators, such as compressive strength, water absorption, density, and abrasion resistance, this research aims to develop an optimized mix design that satisfies SNI requirements while reducing production costs and promoting sustainable waste utilization. The findings are expected to provide a practical and statistically robust framework for industrial-scale paving block manufacturing using red mud as an alternative cementitious material.

Material and methods

Research procedure

The research procedure consisted of material characterization, mix design development, specimen preparation, curing, performance testing, and statistical optimization. This systematic experimental approach is commonly applied in cement-based material optimization studies, particularly in mixture design studies employing response surface-based optimization and factorial design methods (Myers et al., 2016; Meng et al., 2018; Nandurkar et al., 2025).

Materials

Cement. Portland composite cement (PCC) conforming to SNI 15-0302 (BSN, 2004) was used as the primary binder (Neville, 2011; Tw et al., 2023).

Aggregates. Sand and coarse aggregates were obtained from local sources and tested for mud content, moisture content, particle size distribution according to SNI 03-1968 (BSN, 1990), specific gravity, water absorption, and bulk density in accordance with relevant SNI standards (Topçu & Uygunoğlu, 2010).

Red mud. Red mud was sourced from a bauxite processing facility and prepared by air-drying and sieving prior to use. Red mud replacement levels of 0%, 5%, 10%, and 20% by weight of cement were investigated (Power et al., 2011; Huang et al., 2022).

Water. Tap water supplied by the local water utility (PDAM) was used for mixing. The water quality met the general requirements for concrete mixing water (Neville, 2011).

Experimental design using response surface methodology. RSM was employed to model and optimize paving block mixtures with multiple interacting variables. Two independent variables were considered:

- X_1: sand proportion (cement : sand ratios of 1 : 3, 1 : 4, and 1 : 6).
- X_2: red mud replacement level (0–20% by cement weight).

RSM is widely used in cement-based materials research for its ability to generate predictive models and efficiently evaluate interaction effects (Myers et al., 2016; Khayat et al., 2019). The experimental design enabled the development of second-order polynomial regression models for each response.

Specimen preparation. Paving block specimens with dimensions of 200 × 100 × 60 mm were produced using three base mix ratios: 1 : 3 : 0.5, 1 : 4 : 0.5, and 1 : 6 : 0.5 (cement : sand : stone). The water-to-cement ratio was maintained at 0.25 for all mixtures, consistent with paving block production practices (Topçu & Uygunoğlu, 2010; Nofrianto & Hutrio, 2023; Aryanto et al., 2025).

Testing program. The performance of paving blocks was evaluated based on the following tests, conducted in accordance with SNI 03-1968 (BSN, 1990) and SNI 03-0691 (BSN, 1996).

Bulk density measurement. Five specimens (paving blocks) were tested for each mixture to ensure statistical reliability, following common practice in paving block research (Gencel et al., 2012).

Statistical analysis and ANOVA. Analysis of variance (ANOVA) was applied to assess the statistical significance of the developed regression models and interaction terms between red mud content and sand proportion. Model adequacy was evaluated using the coefficient of determination (R^2), adjusted R^2, and lack-of-fit tests at a 95% confidence level (Myers et al., 2016).

Multi-response optimization using desirability function. A desirability function approach was used to simultaneously optimize multiple performance responses. The optimization objectives were defined as follows:

– maximize: compressive strength,
– minimize: water absorption and abrasion.

The desirability-based optimization approach is well established in cementitious material studies for balancing conflicting performance criteria (Meng et al., 2018).

Methodological contribution. The integration of RSM, ANOVA, and desirability function analysis provides a statistically robust framework for optimizing paving block mixtures incorporating industrial waste materials. This methodology enhances mix design efficiency and supports sustainable construction practices through reduced cement consumption and improved material utilization (Montgomery, 2017; Huang et al., 2022).

Results and discussion

Development of response surface models

Second-order polynomial regression models were successfully developed for the selected response variables, namely mechanical strength and durability, using RSM based on a central composite design (CCD). The ANOVA results confirmed that the models were statistically significant at the 95% confidence level, as indicated by model p-values below 0.05. The high values of R^2 and adjusted R^2 further demonstrated good agreement between the experimental and predicted responses, suggesting that the proposed models were able to adequately describe the combined effects of red mud content and sand proportion on paving block performance.

Beyond statistical significance, the adequacy of the models is also supported by their ability to capture the linear, quadratic, and interaction effects of the independent variables. This finding is consistent with findings by Yang et al. (2025), who reported that RSM was effective for optimizing red mud–based cementitious materials because it can account for multi-factor interactions that are often overlooked in conventional one-factor-at-a-time experimental approaches. Their study also highlighted that red mud content was one of the dominant factors affecting both compressive (Oleh et al.,

2022) and flexural performance, which agrees with the present finding that variations in red mud dosage significantly influenced the response behavior of paving blocks.

The observed influence of red mud content on mechanical strength is generally in line with previous studies on red mud-modified concrete. Venkatesh et al. (2021) reported that concrete incorporating red mud achieved maximum compressive strength at approximately 10% replacement, accompanied by reduced porosity, lower water absorption, and improved chloride resistance. Similarly, Sunkpho et al. (2026) found that red mud replacement in the range of 10–15% enhanced compressive strength, flexural strength, and durability, whereas replacement levels above 15% tended to reduce performance. These findings support the present model response, particularly if the optimum red mud content obtained in this study falls within the moderate replacement range of insert optimum red mud content.

However, the present results also indicate that the beneficial effect of red mud is not independent of sand proportion. The significant interaction term between red mud content and sand proportion suggests that the performance of paving blocks is governed not only by the chemical contribution of red mud but also by particle packing, matrix densification, and aggregate–binder balance. This provides a more specific contribution compared with several previous studies that primarily examined red mud as a cement replacement in conventional concrete. For example, recent investigations on red mud concrete reported strength improvement mainly due to filler effects, pozzolanic activity, and densification of the interfacial transition zone, but they did not explicitly evaluate the combined role of red mud and sand proportion in paving block mixtures.

In terms of durability, the present findings are also consistent with earlier reports showing that red mud can improve resistance to water-related deterioration when used at an appropriate dosage. Venkatesh et al. (2021) observed reductions in open porosity, water absorption, sorptivity, and chloride permeability with red mud incorporation, which they attributed to improved microstructure and increased C–S–H gel formation. This supports the durability trend observed in the present study, where insert durability response, e.g., lower water absorption/abrasion loss was achieved at the optimized mixture. Nevertheless, the reduction in performance at excessive red mud levels, if observed, may be attributed to dilution of cementitious phases, increased alkalinity, or insufficient particle bonding, which has also been reported in the literature.

Compared with recent studies on red mud-based geopolymer paver blocks, the present work provides a different but complementary contribution (Mohibullah & Acharya, 2025) demonstrated that red mud–ground blast furnace slag geopolymer paver blocks could satisfy heavy-traffic requirements, with improved mechanical, abrasion, water absorption, carbon, and energy performance compared with conventional concrete paver blocks. While their study focused on geopolymer activation using red mud and slag, the present study focuses on the statistical optimization of red mud content and sand proportion using CCD-RSM. Therefore, the novelty of the present work lies in establishing predictive models that can guide mix proportioning for paving blocks rather than merely identifying a single best-performing mixture.

Overall, the developed RSM models provide a reliable and practical tool for predicting paving block performance within the investigated design space. The agreement between predicted and experimental values indicates that the models are suitable for mixture optimization. More importantly, the results confirm that the use of red mud in paving block production is technically feasible when its dosage is carefully controlled and balanced with the sand proportion. This finding strengthens the potential of red mud valorization in sustainable construction materials while also addressing the limitations noted in previous studies, particularly the need for more systematic optimization of red mud-based paving block mixtures.

In this research, the sand content was maintained at 0.5% for all samples, while the red mud content was set at four levels: 0%, 5%, 10%, and 20%, as illustrated in Table 1. To quantify the variability in the measured responses, including compressive strength, water absorption, and abrasion resistance, each mixture composition was tested in triplicate.

TABLE 1. Model in RSM

No	Sand [%]	Red mud [%]	Compression strength [MPa]	Absorption [%]	Abrasion [mm]	Response
	X_1	X_2	Y_1	Y_2	Y_3	
1	0.5	0	17.61	10.16	0.07	y_1
2	0.5	0	14.51	10.07	0.06	y_2
3	0.5	0	14.34	10.16	0.05	y_3
4	0.5	5	20.52	9.95	0.09	y_4
5	0.5	5	17.69	9.22	0.07	y_5
6	0.5	5	13.02	10.96	0.05	y_6
7	0.5	10	22.96	10.26	0.07	y_7
8	0.5	10	20.24	8.83	0.05	y_8
9	0.5	10	12.24	11.31	0.05	y_9
10	0.5	20	20.41	9.23	0.06	y_{10}
11	0.5	20	19.43	10.58	0.10	y_{11}
12	0.5	20	9.98	11.26	0.15	y_{12}

Source: own work.

Subsequently, Samples 1–3 constitute repeated tests for the mixture containing 0.5% sand and 0% red mud; Samples 4–6 constitute repeated tests for the mixture containing 0.5% sand and 5% red mud; Samples 7–9 constitute repeated tests for the mixture containing 0.5% sand and 10% red mud; and Samples 10–12 constitute repeated tests for the mixture containing 0.5% sand and 20% red mud. Experimental variability during specimen preparation, compaction, curing, and testing is responsible for the variations in response values among samples with equal mixture compositions.

Analysis results of the experiment with RSM surface

The model explains a significant amount of variation in compressive strength (R^2 = 86.44%), though there is some lack of fit as indicated by the significant p-value for the lack-of-fit test (Tables 2–5).

TABLE 2. Analysis of variance (ANOVA) for compressive strength

Specification	Source				
	df	*SS*(adj)	*MS*(adj)	F-value	p-value
Model	5	108.329	21.6659	7.65	0.014
Linear	2	63.290	31.6451	11.18	0.009
Sand [%]	1	62.768	62.7680	22.17	0.003
Red mud [%]	1	0.798	0.7975	0.28	0.615
Square	2	15.221	7.6104	2.69	0.147
Sand [%] × sand [%]	1	0.079	0.0794	0.03	0.873
Red mud [%] × red mud [%]	1	15.141	15.1414	5.35	0.060
Two-way interaction	1	41.989	41.9891	14.83	0.008
Sand [%] × red mud [%]	1	41.989	41.9891	14.83	0.008
Error	6	16.989	2.8315	×	×
Total	11	125.318	×	×	×

Source: own work.

TABLE 3. Model summary

S	R^2	R^2(adj)	R^2(pred)
1.68271	86.44%	75.15%	54.02%

Source: own work.

Regression equation for compression strength:

$$16.4 + 0.93X_1 + 0.370X_2 - 0.088X_1 \cdot X_1 + 0.0253X_2 \cdot X_2 - 0.2028X_1 \cdot X_2 \text{ [MPa]}$$

TABLE 4. Analysis of variance (ANOVA) for absorption

Specification	Source				
	df	*SS*(adj)	*MS*(adj)	F-value	p-value
Model	5	4.54310	0.90862	2.22	0.179
Linear	2	2.64710	1.32355	3.24	0.111
Sand [%]	1	2.48133	2.48133	6.07	0.049
Red mud [%]	1	0.19447	0.19447	0.48	0.516
Square	2	0.87757	0.43878	1.07	0.399
Sand [%] × sand [%]	1	0.83570	0.83570	2.05	0.203
Red mud [%] × red mud [%]	1	0.04187	0.04187	0.10	0.760
Two-way interaction	1	0.82476	0.82476	2.02	0.205
Sand [%] × red mud [%]	1	0.82476	0.82476	2.02	0.205
Error	6	2.45155	0.40859	×	×
Total	11	6.99466	×	×	×

Source: own work.

TABLE 5. Model summary

S	R^2	R^2(adj)	R^2(pred)
0.639212	64.95%	35.74%	0.00%

Source: own work.

Regression equation for absorption:

$$15.04 - 2.47X_1 - 0.137X_2 + 0.285X_1 \cdot X_1 + 0.00133X_2 + 0.0284X_1 \cdot X_2 \text{ [\%]}$$

The model explains a moderate portion of the variance in absorption ($R^2 = 64.95\%$). However, the low predicted R^2 suggests that the model does not generalize well to new data (Tables 6–7).

TABLE 6. Analysis of variance (ANOVA) for abrasion

Specification	Source				
	df	*SS*(adj)	*MS*(adj)	F-value	p-value
Model	5	0.007467	0.001493	4.58	0.046
Linear	2	0.003321	0.001661	5.09	0.051
Sand [%]	1	0.000188	0.000188	0.57	0.477
Red mud [%]	1	0.003166	0.003166	9.70	0.021
Square	2	0.000834	0.000417	1.28	0.345
Sand [%] × sand [%]	1	0.000029	0.000029	0.09	0.777
Red mud [%] × red mud [%]	1	0.000805	0.000805	2.47	0.167
Two-way interaction	1	0.003886	0.003886	11.91	0.014
Sand [%] × red mud [%]	1	0.003886	0.003886	11.91	0.014
Error	6	0.001958	0.000326	×	×
Total	11	0.009425	×	×	×

Source: own work.

TABLE 7. Model summary

S	R^2	R^2(adj)	R^2(pred)
0.0180640	79.23%	61.92%	0.00%

Source: own work.

Regression equation for abrasion:

$$0.165 - 0.0312X_1 - 0.01025X_2 + 0.00167X_1 \cdot X_1 + 0.000185X_2 \cdot X_2 + \\ + 0.001951X_1 \cdot X_2 \text{ [mm·s}^{-1}\text{]}$$

The model explains a significant portion of the variation in abrasion ($R^2 = 79.23\%$), but the low predicted R^2 (0.00%) suggests that the model may not generalize well to new data, although it captures important relationships between factors.

Individual and simultaneous significance tests. By evaluating both individual and simultaneous significance, we gain a comprehensive understanding of how the proportions of red mud and sand influence paving block performance, which is critical for developing optimized sustainable materials in line with performance standards such as SNI 03-0691 (BSN, 1996) and findings by Wang (2025).

According to the Pareto charts, optimal utilization of red clay and sand can enhance the performance of paving blocks, particularly in abrasive resistance, water absorption, and compressive strength. The results of this study suggest that red clay has the potential to be used as a sustainable alternative paving block material without sacrificing quality (Fig. 1). These findings are consistent with the research by Mohibullah and Acharya (2025), who observed that geopolymer paving blocks made from red mud and ground blast furnace slag exhibited excellent mechanical performance and durability. The compressive strength of the blocks exceeded the requirements for heavy traffic, and the water absorption and abrasion values were below the specified limits. The same results were also reported by Zhang et al. (2021), who demonstrated that red mud-based pavement concrete is suitable for road infrastructure due to its good compressive strength, abrasion resistance, and water impermeability. Viyasun et al. (2021) discovered that the tensile properties of concrete can be improved at specific concentrations by substituting red mud, and that water absorption can be reduced in comparison to conventional concrete at specific red mud percentages. As a result, the findings of this study substantiate prior research that the use of red clay as a construction material can facilitate the creation of environmentally friendly pavers while simultaneously satisfying the technical specifications of a variety of applications.

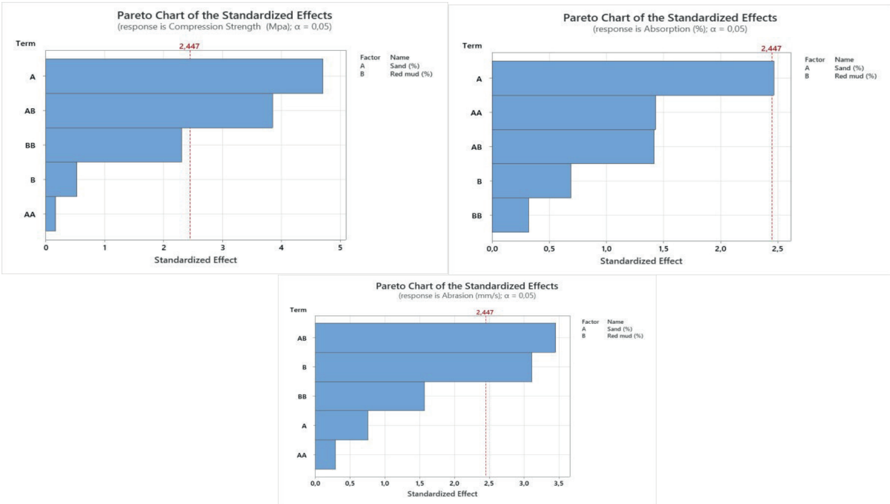

FIGURE 1. Bar chart of the standardized effects for compression strength, absorption, and abrasion
Source: own work.

Model assumption verification. The verification process plays a crucial role in confirming the adequacy of the model for further optimization and prediction.

These findings validate the use of the regression model, making the results from this study reliable for optimization and prediction purposes in the development of paving blocks incorporating red mud and sand (Fig. 2).

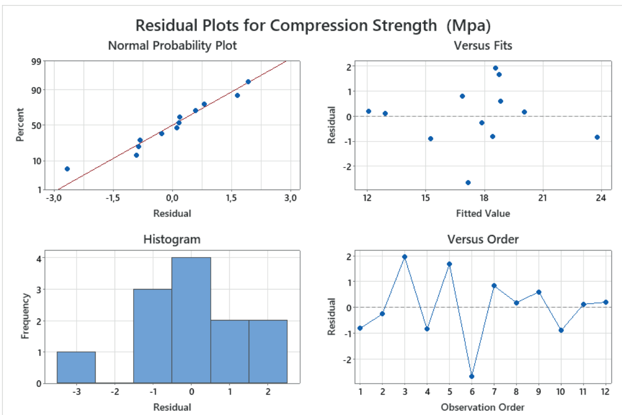

FIGURE 2. Bar chart and residual plot for compression strength
Source: own work.

These findings support the use of the regression model for analyzing absorption, and the results are reliable for optimization and predictions related to paving block performance (Fig. 3).

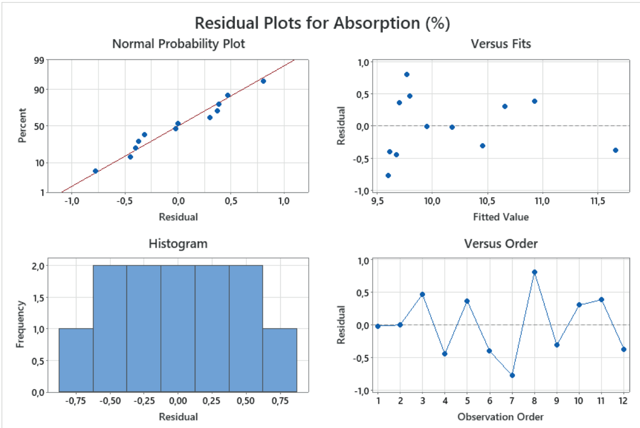

FIGURE 3. Bar chart and residual plot for absorption
Source: own work.

These findings support the use of the regression model for analyzing abrasion and validate the results for optimization and prediction purposes related to paving block performance, water absorption, and a balance (Fig. 4).

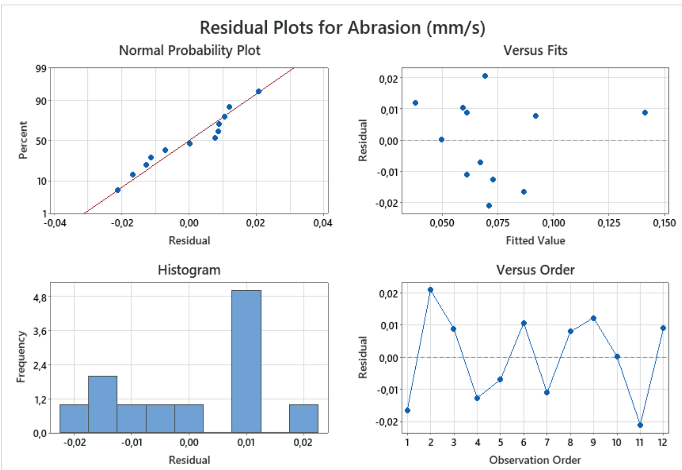

FIGURE 4. Bar chart and residual plot for abrasion
Source: own work.

Response surface and contour plot analysis. Through this analysis we can explore and identify areas on the plot that show the best relationship between sand and red mud composition with the critical properties of paving blocks.

Both the contour and surface plots indicate that increasing sand and red mud content generally enhances compressive strength (Fig. 5). Both the contour and surface plots suggest that the proportion between sand and red mud should be minimized (Fig. 6). Both the contour and surface plots indicate that an optimal combination of sand and red mud results in the best abrasion resistance (Fig. 7).

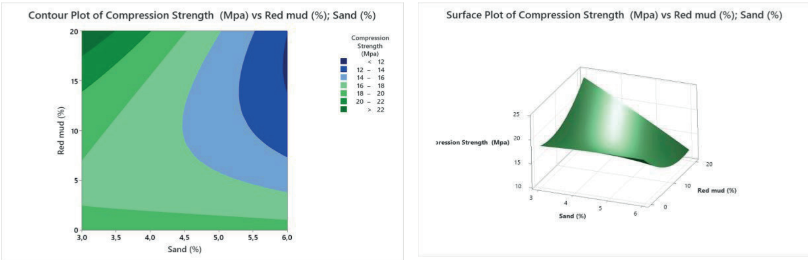

FIGURE 5. Contour and surface plot for compression strength

Source: own work.

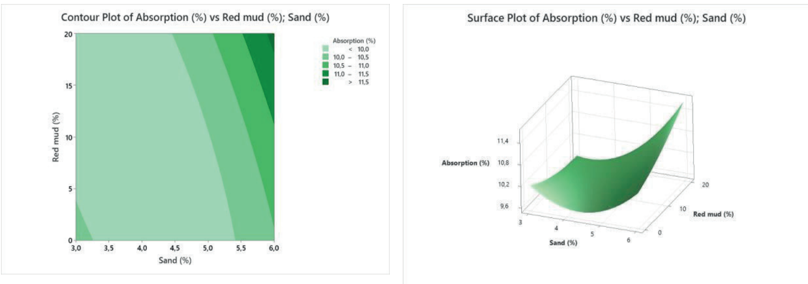

FIGURE 6. Contour and surface plot for absorption

Source: own work.

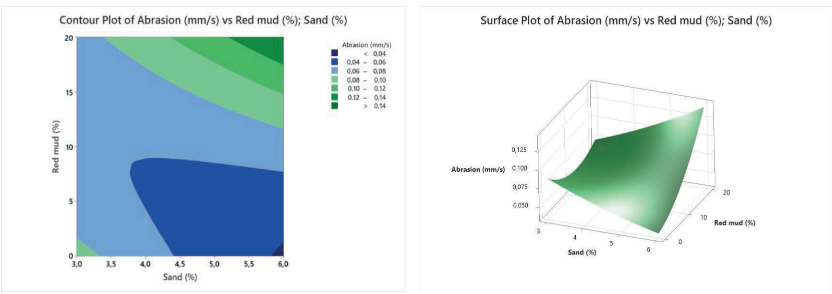

FIGURE 7. Contour and surface plot for abrasion

Source: own work.

Optimization results. In the following analysis we will review the optimized mixture ratios that yield the best results for compressive strength, water absorption, and abrasion resistance. By applying this optimization approach, the paving block production can achieve a balanced and efficient process that meets industry standards.

The minimum abrasion value of y = 0.0694 was obtained at the optimal sand-to-red mud ratio, indicating that the mixture can reduce surface wear and improve the durability of the paving blocks. The desirability value for abrasion was d = 0.80602, which indicates a high level of optimization for this property. In addition, the minimum water absorption value of y = 9.6783 was achieved with a desirability value of d = 0.65716, suggesting that the selected material combination can reduce water absorption to an acceptable level. This is important for improving the long-term performance and durability of paving blocks. Furthermore, the maximum compressive strength value of y = 22.9056 was achieved with a desirability value of d = 0.99502, showing that the combination of sand and red mud can enhance the strength of paving blocks and make them suitable for applications requiring higher load-bearing capacity (Fig. 8).

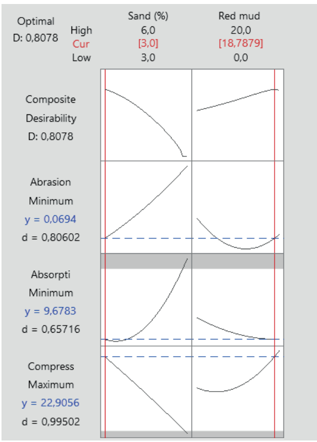

FIGURE 8. Optimum plot

Source: own work.

Validity and implications. This section will examine the validity of the results derived from the optimization model, considering how well the model fits the data and the assumptions made during the analysis. By understanding both the validity of the findings and their implications, manufacturers can make informed decisions on optimizing their production processes for enhanced product performance while achieving sustainability goals (Aslami, 2023).

Figures 9–11 present the comparison between experimental results and RSM predictions for compressive strength, water absorption, and abrasion resistance of paving blocks with varying red mud and sand contents. For compressive strength, the RSM model closely follows the experimental trend, accurately identifying the peak strength region and the subsequent decline at higher replacement levels. Minor deviations occur where experimental values slightly exceed predictions, indicating that the model smooths localized variations arising from material heterogeneity and red mud–cement interactions.

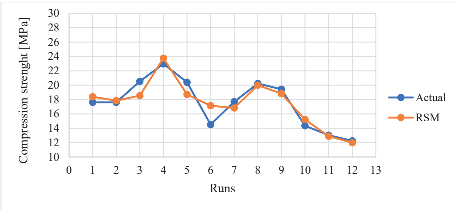

FIGURE 9. Comparison plot of actual compression strength versus response surface methodology prediction

Source: own work.

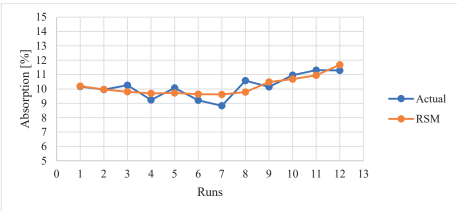

FIGURE 10. Comparison plot of actual compression strength versus response surface methodology prediction

Source: own work.

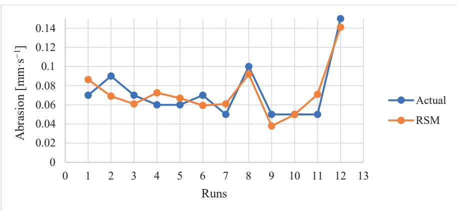

FIGURE 11. Comparison plot of actual compression strength versus response surface methodology prediction

Source: own work.

For water absorption, strong agreement is observed between predicted and measured values, with both showing a consistent and gradual trend. This confirms that RSM effectively captures durability-related responses governed by pore structure and matrix continuity influenced by aggregate gradation and red mud content. Deviations remain within acceptable experimental limits.

In the case of abrasion resistance, the model reproduces the general trend, including increased abrasion loss at higher mix variations. Although slightly larger discrepancies appear at intermediate levels due to the sensitivity of surface integrity and microstructural defects, the predictions remain sufficiently accurate.

Overall, the close correspondence between experimental and predicted responses confirms that RSM is a reliable tool for multi-response optimization of red mud-based paving blocks, despite inherent limitations in modeling complex nonlinear material behavior.

Conclusion

This study confirms the feasibility of utilizing red mud as a partial replacement material in paving block production, in combination with optimized sand proportions, without compromising compliance with SNI 03-0691 requirements (BSN, 1996). Experimental results demonstrate that moderate incorporation of red mud enhances compressive strength while maintaining acceptable water absorption and abrasion resistance, supporting its use as a sustainable alternative material. The developed RSM models exhibit strong predictive capability, as evidenced by the close agreement between experimental and predicted responses, coefficients of determination (R^2 and adjusted R^2) generally exceeding 70–80%, and statistically valid residual distributions. Multi-response optimization using desirability functions, contour plots, and three-dimensional response surfaces identified an optimal mixture with approximately 18.79% red mud replacement and an optimized sand proportion of about 3%. This mixture yielded a 28-day compressive strength of approximately 22.9 MPa, corresponding to SNI Class B, water absorption of about 9.7%, and abrasion loss of approximately 0.07 $mm \cdot s^{-1}$. These performance levels indicate a balanced compromise between mechanical strength and durability. From a practical perspective, the optimized mixture is suitable for pedestrian and parking-area paving applications in tropical urban environments. Nevertheless, localized deviations between experimental and predicted values, particularly at higher red mud contents, highlight the limitations of RSM in capturing highly nonlinear material behavior. Therefore, the optimized range should be respected in practical implementation.

Future studies should investigate the long-term durability of red mud-based paving blocks under aggressive exposure conditions, including freeze–thaw cycles, sulfate attack, and carbonation, to better predict service life (Jaya et al., 2025). Additionally, life cycle assessment (LCA) and cost–benefit analysis are recommended to quantify the environmental and economic advantages of red mud utilization compared with conventional paving blocks. Finally, further research should focus on scaling up the optimized mix design to pilot-scale and field-produced paving blocks to evaluate manufacturing consistency, quality control, and in-service performance under real construction conditions.

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Summary

Multi-response optimization of red mud and sand proportions in paving block production via response surface methodology (RSM). Rising cement and natural aggregate prices have intensified the need for sustainable and optimized paving block mixtures incorporating industrial by-products. This study investigates the multi-response optimization of red mud and stone content in paving block production using response surface methodology (RSM). Red mud, an alkaline by-product of the bauxite refining industry, was utilized as a partial cement replacement to reduce material consumption and environmental impact. The objective was to determine the optimal proportions that satisfy the performance requirements of SNI 03-0691-1996. An RSM-based experimental design evaluated the interactive effects of red mud substitution (0–20% by cement weight) and stone proportion on compressive strength, bulk density, water absorption, and abrasion resistance. Specimens were produced using portland composite cement, sand, stone, water, and pre-treated red mud. Regression models and response surface plots were developed for prediction and optimization. Results indicate that approximately 18.79% red mud replacement with an optimized aggregate proportion yields the best overall performance. The optimized mix achieved a 28-day compressive strength of 22.91 MPa, satisfying SNI class B criteria, while demonstrating reduced water absorption and abrasion loss. This study introduces a statistically robust multi-response RSM approach for sustainable paving block mix design.

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Material and environmental performance of breakwaters with varying slopes and concrete armor types

Keywords: breakwater design, hydraulic stability, sustainable coastal engineering, embodied carbon, concrete armor

Introduction

Global climate change has intensified the need for scientists and engineers to design and construct environmentally friendly, sustainable coastal structures. In the coming decades, littoral areas are expected to face increasingly severe challenges, including higher design waves, unexpected overtopping, and greater risks of coastal flooding due to structural damage (Chen et al., 2025; Cunha et al., 2025; Gazi et al., 2025; Yuan et al., 2025). Breakwaters play a crucial role in coastal protection by mitigating the impact of wave action, thereby reducing the risk of flooding and coastal erosion. Their primary function is to dissipate wave energy, alleviate currents, and facilitate sediment deposition, which promotes beach formation and shoreline stability (Du et al., 2025; Fotopoulos et al., 2025; Yuksel et al., 2025).

Various types of breakwaters are widely employed in coastal engineering, such as detached and attached breakwaters or caisson-type structures constructed using materials, including concrete blocks, rock, and steel. Traditionally, the primary layer of breakwaters has been constructed using large natural stones to resist wave forces effectively. However, the availability of natural stones of suitable size and quality is becoming increasingly limited in many coastal regions because of resource depletion and environmental restrictions on quarrying activities. This scarcity has driven a shift toward mass concrete armored units that can be fabricated in controlled shapes, such as tetrapods, dolos, and tribars, tailored for optimal interlocking and wave energy dissipation. These engineered concrete units have become a popular and practical alternative in modern breakwater construction, offering consistent performance and adaptability to diverse design requirements (Anastasaki et al., 2016; Sukcharoen et al., 2024; Gísladóttir et al., 2025; Wijesekara et al., 2025).

However, the widespread use of concrete in breakwater construction has raised significant sustainability concerns. Concrete, which is the most widely used construction material, exemplifies this dilemma. Figure 1 illustrates several types of concrete armor units commonly employed for coastal protection. Among these, the earliest and most recognized is the tetrapod, which was developed in 1950 by Pierre Danel and Paul Anglès d'Auriac at the Laboratoire Dauphinois d'Hydraulique (now Artelia) in Grenoble, France. The tetrapod is a purpose-designed concrete block for wave energy dissipation, specifically engineered to resist coastal erosion in structures such as breakwaters and seawalls (Kim & Suh, 2013; Park et al., 2014; Mitsui et al., 2023). Its unique interlocking geometry enhances the stability by effectively dissipating wave forces and minimizing the displacement of individual units. This innovative design represents a significant advancement in coastal engineering and has since been widely adopted worldwide for shoreline protection.

While its mechanical versatility and the global abundance of its feedstocks underlie its prevalence, the manufacture of its binding agent, portland cement, is responsible for approximately 8% of worldwide CO_2 emissions (Ishak & Hashim, 2015; Lehne & Preston, 2018; El-Gamal et al., 2023; Keintjem et al., 2024). As vital infrastructure, breakwaters protect coastlines, harbors, and marine installations from the prolonged forces of wave action, thereby maintaining regional structural stability and supporting the ecological balance. Given the high cost, substantial material consumption, and long-term durability challenges associated with traditional breakwater construction, it is essential to explore innovative and sustainable design solutions. In particular, optimizing armor unit shapes and breakwater slopes to improve material efficiency and reduce embodied carbon represents a promising pathway toward more sustainable coastal infrastructure.

FIGURE 1. Concrete armor units commonly used in rubble mound breakwaters: (a) tetrapod, (b) tribar, and (c) dolos

Source: own work.

Armor erosion caused by wave attacks is recognized as one of the primary failure modes in the design of mound breakwaters. Consequently, the hydraulic stability of the armor layer has been the subject of extensive research in recent decades. Hanzawa et al. (2012) investigated the stability of concrete armor blocks subjected to solitary wave conditions through hydraulic model experiments on breakwaters composed of wave-dissipating units. Similarly, Maruyama et al. (2014) and Mitsui et al. (2016) conducted hydraulic model tests and numerical analyses to examine the stability of armor units positioned behind composite breakwaters under overflowing tsunami waves. Safari et al. (2018) analyzed the hydraulic stability of Starbloc armor units and evaluated their influence on overtopping performance. Mares-Nasarre et al. (2022) performed physical model tests to assess the stability of cube-armored mound breakwaters in depth-limited breaking wave conditions, demonstrating that their observed stability was lower than predictions based on existing empirical formulas. Aiming to enhance breakwater stability while reducing construction costs and material usage, Yuksel et al. (2022) explored the performance of high-density cubes in the armor layers. These studies represent only a few examples of experimental and numerical investigations conducted to characterize the hydraulic behavior of armor units used in breakwater design.

Although numerous studies have examined the hydraulic stability of armor units under various wave conditions, most have focused on individual armor shapes or single slope configurations, with limited comparative assessments across multiple armor types and slopes. Furthermore, the integration of embodied carbon analysis into breakwater design has been largely overlooked, despite its growing importance for sustainable infrastructure. Therefore, this study aims to investigate the design efficiency of breakwaters constructed with different types of concrete armor units, quantifying the required material volumes and associated embodied carbon to identify optimal configurations that balance hydraulic stability, material efficiency, and environmental impact.

Methodology

This study investigates the design efficiency of breakwaters constructed with three concrete armor unit types – tetrapods, tribars, and dolos – across three slope configurations: 1 : 1.5, 1 : 2, and 1 : 3. The methodology involves determining the required armor unit weight and quantity for each slope–armor combination using empirical stability equations, calculating the total material volume, and assessing the associated embodied carbon emissions. This study focuses on the design and performance of the main armor layer because its hydraulic stability is a key factor in ensuring breakwater effectiveness under wave attack. The assessment is limited to the material efficiency and environmental performance of the armor layer; aspects related to wave attenuation effectiveness and the structural durability of individual armor units are not explicitly evaluated and are considered outside the scope of this study.

The general cross-sectional configuration of the rubble mound breakwater used in this study is illustrated in Figure 2. The breakwater consists of a central core, an underlayer filter, and an outer armor layer constructed with concrete armor units. The slope of the armor layer varies according to the three configurations investigated. Key geometric parameters of the breakwater include the armor layer thickness, which is determined based on the size of the selected armor units, and the structure height, extending from the seabed level (E_{SB}) at −8.0 m to a crest level designed to prevent overtopping under the design wave conditions.

Hydrodynamic design parameters were established to reflect typical severe storm conditions, and a significant wave height (H) of 3.0 m and a peak wave period (T) of 10 s were adopted for the stability calculations. Water level variations are defined by the high water level (HWL) at +1.85 m, mean water level (MWL)

at +1.05 m, and low water level (*LWL*) at +0.30 m relative to chart datum. These values ensure that the analysis considers the most critical scenarios for armor stability, including the maximum expected wave attack combined with high water levels, which may increase overtopping risks. The adopted parameters provide a consistent and realistic basis for evaluating the performance of different armor types and slope configurations under severe coastal conditions.

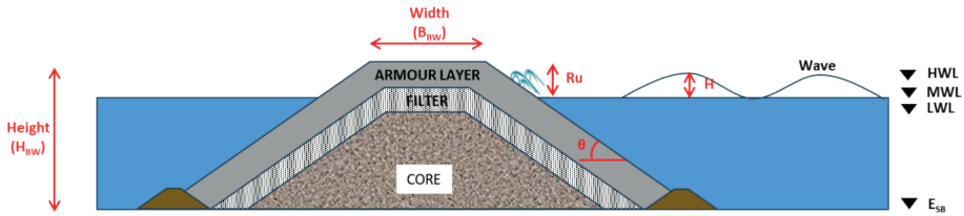

FIGURE 2. Breakwater configuration used in this study
Source: own work.

The design of the armor layer followed established empirical methods to ensure hydraulic stability under the adopted design wave conditions. The procedure consists of determining the breakwater crest elevation, calculating the required armor unit weight, and estimating the number of armor units needed to achieve the specified layer thickness and stability.

The total height of the breakwater crest (H_{BW}) was determined to prevent overtopping under the design wave conditions. This value was calculated using the following equation:

$$H_{BW} = E_{SB} + HWL + Ru + 0.5 \tag{1}$$

where: E_{SB} is the elevation of seabed level, HWL is the high water level, Ru is the wave run-up and 0.5 m is the additional freeboard for safety.

The wave run-up (Ru) was estimated based on the Iribarren number (I_r), which characterizes the slope and wave steepness using empirical relationships between I_r and the relative wave run-up (Ru/H), as presented in Figure 3. The Iribarren number (I_r) is calculated as follows:

$$I_r = \frac{\tan\theta}{\sqrt{H / L_0}} \tag{2}$$

where: θ is the slope angle of the breakwater, H is the design wave height and L_0 is the deepwater wavelength, given by

$$L_0 = 1.56T^2 \tag{3}$$

where: T is the peak wave period.

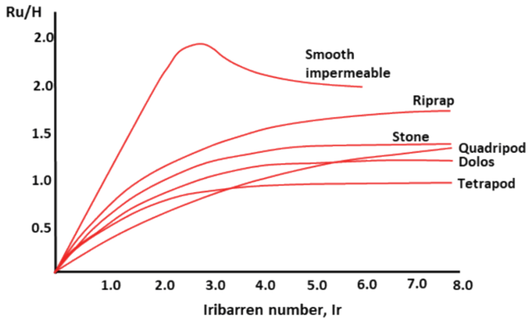

FIGURE 3. Iribarren number (I_r) and relative wave run-up (Ru/H) curves for different types of armor
Source: Triatmodjo (2016).

The required armor unit weight (W) is calculated using Hudson's formula (Hudson, 1959), which ensures stability against wave forces:

$$W = \frac{\gamma_r H^3}{K_D \left(\gamma_r / \gamma_a - 1 \right)^3 \cot \theta} \tag{4}$$

where: γ_r and γ_a are the unit weights of the armor material (concrete) and seawater, respectively, and K_D is the stability coefficient, which depends on the armor unit type (values provided in Table 1).

The width of the breakwater crest (B_{BW}) was calculated to accommodate the minimum number of armor units, ensuring sufficient layer thickness and structural stability. It is given by:

$$B_{BW} = nk_\Delta \left(\frac{W}{\gamma_r} \right)^{\frac{1}{3}} \tag{5}$$

where: n is the number of armor units across the crest (typically above 3) and k_Δ is the layer coefficient, dependent on the armor type, as shown in Table 1.

The total number of armor units required per armor layer area (N) was determined to ensure complete coverage, taking into account the armor porosity. It is calculated using:

$$N = Ank_\Delta\left(1-\frac{P}{100}\right)\left(\frac{\gamma_r}{W}\right)^{2/3} \tag{6}$$

where: A is the layer plan area, and P is the porosity percentage of the armor layer (values in Table 1).

TABLE 1. Stability coefficient for different armor types

Armor	Stability coefficient (K_D) [-]	Layer coefficient (k_Δ) [-]	Porosity (P) [%]
Tetrapod	8.0	1.04	50
Tribar	10.0	1.13	54
Dolos	31.8	1.0	63

Source: Triatmodjo (2016).

In this study, the armor units were assumed to be constructed from plain unreinforced mass concrete. This approach reflects the standard practice for armor units of moderate size (up to approximately 2–3 t), where the risk of structural failure due to tensile stresses is minimal under typical handling and hydraulic loading conditions. Moreover, avoiding reinforcement reduces both material costs and the overall environmental footprint of the breakwater, aligning with the objective of identifying material-efficient and low-carbon design solutions.

The embodied carbon assessment for the armor units in this study was conducted using a ‘cradle-to-gate’ framework, encompassing life cycle stages A1–A3 as defined in BS EN 15978 (British Standards Institute [BSI], 2011). The total embodied carbon (EC) associated with each design scenario was calculated using the following equation:

$$EC = \sum\left(C \cdot CF\right) \tag{7}$$

where: C is the quantity of concrete material used [kg] and CF is the embodied carbon factor, taken as 0.138 kg CO_2e·kg^{-1}.

This carbon factor corresponds to concrete grade C32/40, which is widely employed in marine structures, and was established based on a comprehensive carbon and energy inventory compiled using the circular ecology approach (Circular Ecology, n.d.). This methodological approach adheres to recognized standards for life cycle assessment, ensuring a consistent and robust evaluation of the carbon footprint associated with the production of concrete armor units from raw material extraction to the completion of manufacturing processes at the factory gate.

Results and discussion

This section presents and analyzes the calculated armor unit requirements, total material quantities, and embodied carbon estimates for each slope-armor combination investigated. The results allow a comparative assessment of the design efficiency across the three armor unit types – tetrapods, tribars, and dolos – under three breakwater slope configurations of 1 : 1.5, 1 : 2, and 1 : 3. The discussion highlights trends in the required armor sizes, number of units, total material volume, and their implications for embodied carbon, stability performance, and sustainable breakwater design.

Figure 4 presents the required armor unit weights for each armor type (tetrapods, tribars, and dolos) across the three investigated slope configurations (1 : 1.5, 1 : 2, and 1 : 3). The results show a clear trend: as the slope becomes gentler, the required individual armor unit weight decreases substantially for all armor types. These trends reflect the fundamental relationship between the slope angle and wave energy dissipation: gentler slopes spread the wave energy over a larger area, reducing the forces acting on individual armor units and allowing for smaller units to achieve hydraulic stability. Among the three armor types, dolos consistently requires the lowest individual unit weights for all slope configurations, which aligns with their high stability coefficient (K_D) and superior interlocking performance. This highlights the potential for significant material and embodied carbon savings when dolos are used, particularly when combined with gentler slopes. However, these material advantages should be weighed against practical considerations such as placement complexity and potential breakage risk during construction.

The calculated total crest height of the breakwater, determined using the design wave conditions and run-up calculations, was consistently 13 m above the seabed level for all armor types and slope configurations. This consistent crest height ensures comparable protection against overtopping across design scenarios, allowing a direct assessment of other geometric parameters, such as crest width.

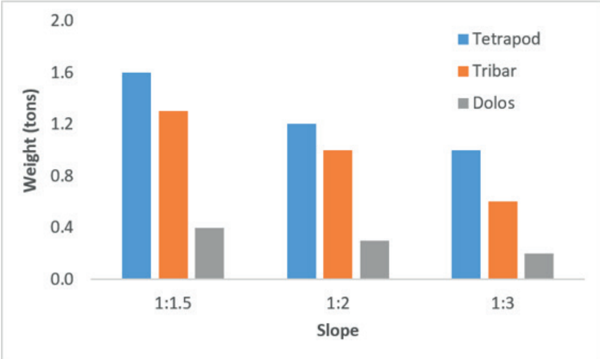

FIGURE 4. Required armor unit weights for tetrapods, tribars, and dolos across different breakwater slope configurations

Source: own work.

Figure 5 presents the required widths of breakwater crests for tetrapods, tribars, and dolos across the three investigated slopes. The results indicated that the crest width generally decreased as the slope became gentler. For example, in the tetrapod case, the crest width reduced from approximately 2.6 m at a 1 : 1.5 slope to 2.1 m at a 1 : 3 slope. A similar trend was observed for tribars and dolos, with dolos consistently requiring the narrowest crest widths across all the slopes. This is attributed to the higher stability coefficient (K_D) of dolos, which allows fewer and smaller units to achieve the required layer thickness, thereby reducing the required crest width.

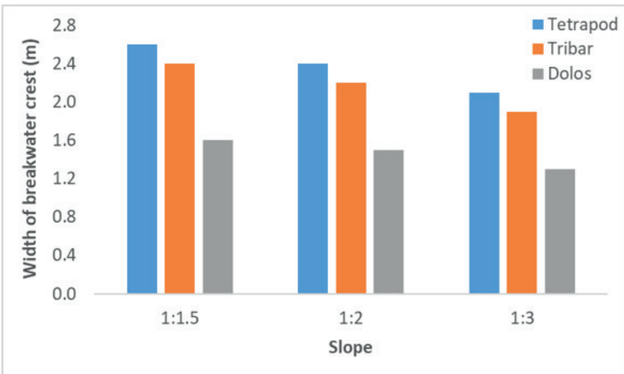

FIGURE 5. Required breakwater crest widths for tetrapods, tribars, and dolos across different slope configurations

Source: own work.

These findings imply that selecting armor units with higher hydraulic stability not only minimizes the required material volumes but also allows more compact crest dimensions. This can be advantageous in projects with limited spatial availability or where minimizing the footprint of the structure is a priority. However, as with armor weight reduction, these geometric benefits must be balanced with practical considerations related to construction feasibility, placement accuracy, and long-term maintenance.

Figure 6 shows the calculated number of armor units required per 10 m² of armor layer area for tetrapods, tribars, and dolos across the three slope configurations. The results reveal a clear trend: as the slope becomes gentler from 1 : 1.5 to 1 : 3, the number of armor units required per unit area increases significantly for all armor types. For example, the number of tetrapod units per 10 m² increased from 15 units on a 1 : 1.5 slope to 24 units on a 1 : 3 slope. Similarly, tribars increased from 16 to 25 units, while dolos showed the largest increase, from 27 to 42 units, over the same slope range.

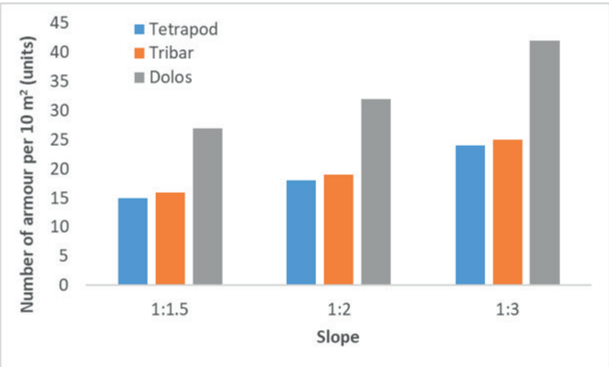

FIGURE 6. Required number of armor units for tetrapods, tribars, and dolos across different slope configurations

Source: own work.

This increase in the number of units with gentler slopes is expected because a flatter slope expands the surface area of the armor layer, thus requiring more units to maintain the necessary layer thickness and porosity. Among the three armor types, dolos consistently requires the highest number of units per area on each slope, despite their smaller individual unit sizes. While the high stability coefficient of dolos allows smaller units to achieve hydraulic stability, their interlocking geometry requires a greater quantity of units to form a stable layer.

These findings highlight an important trade-off: although gentler slopes with efficient armor types such as dolos reduce individual unit weight and total material mass, they also lead to a substantial increase in the number of units to handle and place. This can complicate construction logistics and increase placement time and costs. Therefore, practical considerations, such as available construction resources, placement accuracy, and long-term maintenance, should be carefully evaluated when selecting slope configurations and armor types.

While the preceding discussions have detailed the required armor unit weights, crest widths, and number of armor units necessary for each slope and armor type, a comprehensive evaluation of breakwater design efficiency must also account for environmental impacts. The use of concrete in armor units contributes substantially to the overall carbon footprint of coastal structures, given the high emissions associated with portland cement production. Therefore, in addition to assessing material quantities, this study evaluates the embodied carbon associated with each slope-armor combination to provide a more holistic understanding of the sustainability implications of breakwater design choices. The results of the embodied carbon calculations are presented in Figure 7.

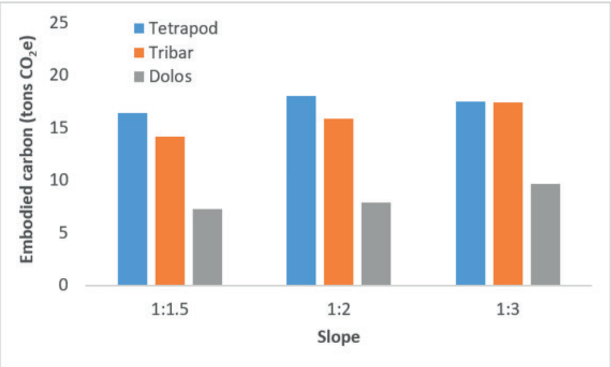

FIGURE 7. Embodied carbon emissions per meter length of breakwater across different slope configurations

Source: own work.

The results show that embodied carbon increases consistently as the slope becomes gentler from 1 : 1.5 to 1 : 3 for all armor types. For example, in the tetrapod case, the embodied carbon increases from approximately 16 t CO_2e at a 1 : 1.5 slope to over 22 t CO_2e at a 1 : 3 slope. A similar trend was observed for tribars, which increased from approximately 14 to 18 t CO_2e, while dolos showed the lowest embodied carbon across all slopes, rising from approximately 7 t CO_2e to 10 t CO_2e.

Although embodied carbon is calculated using a constant carbon factor (0.138 kg $CO_2e \cdot kg^{-1}$) and is therefore linearly proportional to concrete mass, the trend observed in Figure 7 differs from that shown in Figure 4 because the two figures represent different mass bases. Figure 4 presents the required weight of individual armor units, which decreases as the slope becomes gentler. In contrast, Figure 7 reflects the total embodied carbon per meter length of breakwater, which depends on the total concrete volume required to construct the armor layer.

For gentler slopes, while smaller individual armor units are sufficient to maintain hydraulic stability, the surface area of the armor layer per meter length increases substantially. This leads to a significantly higher number of armor units, as shown in Figure 6, and consequently a larger total concrete volume. As a result, the total embodied carbon increases with gentler slopes despite the reduction in individual unit weight. Similar trade-offs between armor unit size, quantity, and overall material demand have been reported in previous hydraulic studies focusing on armor stability and slope effects (Hanzawa et al., 2012; Maryuama et al., 2014; Mitsui et al., 2016; Safan et al., 2018; Mares-Nasarre et al., 2022; Yuksel et al., 2022). However, those studies primarily addressed hydraulic performance, whereas the present results extend this body of knowledge by demonstrating that slope geometry and armor type selection also exert a significant influence on the carbon footprint of breakwater structures.

Despite the increase in total material demand for gentler slopes, dolos consistently result in substantially lower embodied carbon than tetrapods and tribars across all slope configurations. This advantage is attributed to the high stability coefficient of dolos, which enables the use of smaller unit sizes and lower total concrete volumes, even when accounting for the increased number of units. These findings highlight the importance of jointly considering slope geometry, armor type, and total material demand when aiming to minimize the environmental impact of rubble mound breakwaters.

Conclusion

In this study, the design efficiency of rubble mound breakwaters armored with three types of concrete armor across three slope configurations (1 : 1.5, 1 : 2, and 1 : 3) was investigated. The analysis focused on the required armor unit sizes, number of units per area, crest geometry, and embodied carbon emissions to identify optimal combinations for material efficiency and sustainability.

The results showed that gentler slopes significantly reduced the required individual armor unit weights owing to the decreased wave energy per unit area. However, flatter slopes simultaneously increased the number of armor units required per unit area as the armor layer surface area expands. Dolos consistently demonstrated the highest material efficiency, requiring the smallest individual unit sizes, and resulting in the lowest total concrete volumes and embodied carbon across all slope configurations. In contrast, tetrapods and tribars demanded larger total volumes and generated higher embodied carbon emissions, particularly on gentler slopes.

Despite these material and environmental advantages, the increased number of armor units associated with flatter slopes, especially for dolos, can introduce practical challenges during construction, including more complex placement logistics and potentially higher labor costs. These findings underscore the importance of balancing the hydraulic stability, material efficiency, and embodied carbon considerations with practical construction constraints.

Overall, this study highlights that selecting high-efficiency armor units, such as dolos, combined with appropriately optimized slope configurations, offers a viable strategy for reducing material consumption and carbon footprint in breakwater design. Integrating embodied carbon assessments into the early stages of coastal infrastructure planning provides valuable insights into achieving more sustainable, cost-effective, and resilient shoreline protection solutions.

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Data availability

Data analysis https://zenodo.org/records/15795932

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Summary

Material and environmental performance of breakwaters with varying slopes and concrete armor types. Global climate change and resource scarcity have intensified the need for sustainable and resilient coastal protection. Breakwaters, which dissipate wave energy and mitigate shoreline erosion, traditionally rely on large natural stones or mass concrete armor units. However, the increasing unavailability of suitably sized natural stones and significant carbon emissions associated with concrete production present critical challenges for sustainable design. This study aimed to investigate the design efficiency of rubble mound breakwaters armored with three types of concrete units (tetrapods, tribars, and dolos) across three slope configurations (1 : 1.5, 1 : 2, and 1 : 3). The methodology involved calculating the required armor unit weight and quantity using Hudson's equation, determining the crest geometry, and estimating the total embodied carbon emissions per meter length of breakwater based on a cradle-to-gate life cycle assessment approach. The results show that while gentler slopes reduce individual armor unit weight, they increase the number of units required per area, leading to higher total material use and embodied carbon. Among the armor types, dolos consistently exhibited the highest material efficiency and lowest embodied carbon because of their superior stability coefficient, although they require more units for placement. These findings highlight the trade-offs between slope geometry, armor type, and environmental performance, emphasizing the importance of integrated design approaches for optimizing material consumption and carbon footprint in sustainable breakwater construction.

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Behavioral drivers of green bond investment for renewable energy and sustainable infrastructure: a Costa Rican study with Central American implications

Keywords: green bonds, sustainable finance, behavioral finance, theory of planned behavior, value-belief-norm theory, investor behavior

Introduction

Climate change and environmental degradation underscore the need for aligning economic growth with planetary limits. Green bonds have emerged as a leading mechanism to finance renewable energy, energy-efficient buildings, sustainable transportation systems, and other environmental engineering projects (Sahu et al., 2024). Global issuance has expanded rapidly, supported by stronger standards and disclosures, while green bonds are increasingly viewed as a tool for advancing national climate targets (Ghaemi Asl & Shahzad, 2025; Kumar et al., 2025). Evidence also shows that investors sometimes accept lower yields, resulting in a "greenium" that reflects pro-environmental preferences in fixed-income pricing (Green & Roth, 2025).

Costa Rica offers a compelling case to examine retail investors' willingness to invest in green bonds. Its National Decarbonization Plan 2018–2050 outlines sectoral transitions aimed at reducing emissions while sustaining growth (Okot et al., 2021). Mobilizing domestic savings held by individuals is essential, yet retail participation in green bonds remains limited, raising questions about awareness, access, and psychosocial drivers (Kumar et al., 2025). Understanding these drivers is crucial to broadening the investor base needed to achieve national sustainability goals (Chishti et al., 2025).

Research problem and relevance

If banked consumers are unaware of, uncertain about, or unable to access green bonds, a significant pool of domestic climate capital remains untapped. This study addresses this issue by analyzing the psychosocial determinants of Costa Rican retail investors' intention to invest in green bonds, thereby informing targeted interventions such as investor education, simplified access, and enhanced disclosures (Mesthrige et al., 2020; Bocquet et al., 2021). Research questions include:

- RQ1: What is the level of awareness and knowledge of green bonds among Costa Rican retail investors?
- RQ2: How do they perceive the financial and environmental features of green bonds?
- RQ3: How willing are they to invest, and under what conditions?
- RQ4: Which socio-psychological factors best explain their intention to invest?

To answer these questions, we integrate the theory of planned behavior (TPB) and the value-belief-norm (VBN) framework. TPB posits that intention is driven by attitude, subjective norms, and perceived behavioral control (Ajzen, 1991). In investment contexts, favorable attitudes, supportive norms, and greater perceived behavioral control (PBC), facilitated by knowledge, access, and low minimum investment amounts, should strengthen intention. The VBN framework highlights moral and value-based drivers, whereby biospheric/altruistic values shape beliefs, activate personal moral norms, and drive pro-environmental action (Dreifert & Rigotti, 2025; Naga, 2025).

Integrating TPB and VBN allows us to capture both instrumental (attitudes, norms, efficacy) and normative (values, beliefs, moral obligation) pathways to green bond investment. Prior evidence shows that combined models explain behavior better than single theories (Dreifert & Rigotti, 2025). Furthermore, credible labeling and transparency reinforce investor trust, strengthening attitudes and beliefs toward green bonds (Ghaemi Asl & Shahzad, 2025). Proposed hypotheses are as follows (Fig. 1):

– H1: Attitude → Intention (Ajzen, 1991).
– H2: Subjective Norm → Intention (Ajzen, 1991).
– H3: PBC → Intention (Ajzen, 1991).
– H4: Values/Beliefs → Personal Norm (Dreifert & Rigotti, 2025).
– H5: Personal Norm → Intention (Dreifert & Rigotti, 2025).
– H6: Market Credibility → Attitudes/Beliefs (Saravade et al., 2025).

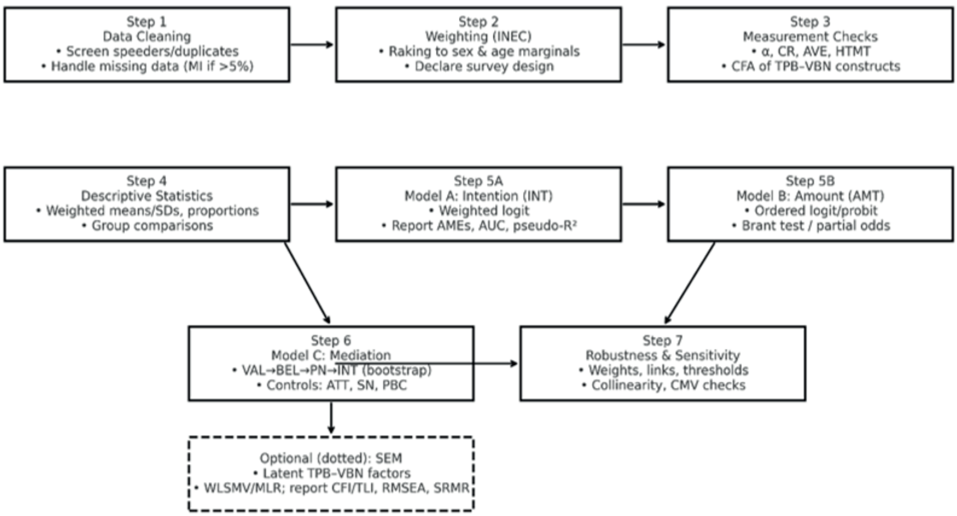

FIGURE 1. Integrated TPB–VBN model of green bond investment intention. Solid arrows represent hypothesized direct effects (H1–H5); dotted arrows indicate exploratory credibility links (H6)

Source: own work.

Material and methods

Study design and sampling

We conducted a quantitative, cross-sectional, explanatory survey of adult Costa Rican residents with access to banking services to assess their willingness to invest in green bonds and identify the psychosocial determinants, integrating the TPB and VBN framework (Ajzen, 1991; Dreifert & Rigotti, 2025). The target population comprised Costa Rican residents aged 18+ with access to the formal financial system. Inclusion criteria were residence in Costa Rica, legal age, self-reported banked status, and informed consent. Exclusion criteria included duplicate entries and inattentive completions. Participants were recruited using nonprobability convenience sampling via institutional lists and social and professional networks. The final sample size was n = 387, sufficient to achieve ≥0.80 statistical power to detect average marginal effects of 0.08–0.10 in logistic models with 6–8 predictors (Tutz, 2022).

Post-stratification weighting

To improve representativeness, we calibrated the sample to the adult population marginals reported by National Institute of Statistics and Census (INEC, 2023) by sex and age groups. Weighting factors are reported in Table 1, showing a slight underrepresentation of women and older adults. Final survey weights reflect joint calibration across both dimensions.

TABLE 1. Post-stratification marginals and raking weights (INEC targets versus assumed sample profile)

Category	Target [%] (INEC, 2023)	Assumed sample [%]	Weight factor (target/sample) [-]
		Sex	
Male	49.96	57.00	0.876
Female	50.04	43.00	1.164
		Age (adults 18+)	
18–35	38.62	55.00	0.702
36–64	47.35	38.00	1.246
65+	14.02	7.00	2.003

Population structure by sex and age groups; adult age targets are renormalized to ages 18+ years.

Source: own work based on survey responses.

Although post-stratification weighting improves alignment with population margins, the nonprobability design limits full generalizability of the findings. The findings should therefore be interpreted as exploratory.

Measures and operationalization

All constructs used seven-point Likert scales (1 = strongly disagree, 7 = strongly agree). TPB included Attitude (ATT), Subjective Norm (SN), and Perceived Behavioral Control (PBC) (Ajzen, 1991). VBN included Values (VAL), Beliefs (BEL), and Personal Norm (PN) (Dreifert & Rigotti, 2025). We also measured Credibility (CRED) of green bonds (Ge et al., 2025), Literacy (LIT), and Investing Experience (EXP). Outcomes were intention (INT_high ≥5/7) and investment amount (AMT) (Table 2).

TABLE 2. Construct operationalization and projected scale properties

Construct	Example stems (seven-point Likert)	# items	Score	α	CR	AVE	Source
ATT	"Green bonds are a good idea/beneficial/fit my goals."	4	Mean	0.86	0.87	0.63	Ajzen (1991)
SN	"Important others approve/expect me to invest."	4	Mean	0.82	0.84	0.57	Ajzen (1991)
PBC	"I have knowledge/means; small tickets available."	4	Mean	0.81	0.83	0.55	Ajzen (1991)
VAL	"Protecting nature guides my decisions."	4	Mean	0.85	0.87	0.60	Dreifert and Rigotti (2025)
BEL	"My investments can help the environment." (AC/AR)	5	Mean	0.80	0.82	0.54	Dreifert and Rigotti (2025)
PN	"I feel morally obliged to support green projects."	4	Mean	0.84	0.86	0.59	Dreifert and Rigotti (2025)
CRED	"Certification/reporting makes me trust this bond."	4	Mean	0.83	0.85	0.58	Ge et al. (2025)
LIT	Two quiz items + one self-efficacy item	3	Sum/ /Mean	0.66	0.67	×	×

Source: own work based on survey responses.

Data collection and statistical analysis

The online survey (8–12 min) began with an informed consent form. No identifying information was collected. Quality checks included time thresholds, one attention check, and duplicate removal (Table 3). Missing data were handled via listwise deletion (≤5%) or multiple imputation (m = 20) under MAR assumptions (Raheem, 2023).

TABLE 3. Variable descriptions, descriptive statistics, and hypothesized relationships

Construct	Description/Coding	Mean (SD) or %	Hypothesis (Path)
INT_high	Intention to invest (1 if ≥5 on 1–7 scale)	46%	Outcome (H1, H2, H3, H5)
AMT	Investment amount bracket (ordinal)	Median = 2–3	Outcome (scale analysis)
ATT	Attitude (1–7 index)	4.90 (1.10)	H1: ATT → INT
SN	Subjective norm (1–7 index)	4.60 (1.20)	H2: SN → INT
PBC	Perceived behavioral control (1–7 index)	4.30 (1.30)	H3: PBC → INT
VAL	Biospheric/Altruistic Values (1–7 index)	5.20 (1.00)	H4: VAL → BEL → PN
BEL	Ecological beliefs (1–7 index)	5.00 (1.10)	H4: VAL → BEL → PN
PN	Personal norm (1–7 index)	4.70 (1.20)	H5: PN → INT
CRED	Credibility of green bond labels (1–7 index)	4.10 (1.20)	H6: CRED → ATT/BEL → INT
LIT	Financial literacy (0–3)	1.60 (0.90)	Control variable
EXP	Prior investing experience (1 = yes)	49%	Control variable

n = 387 for all variables. SD is reported for continuous variables. Hypotheses are tested using logistic regression (INT_high) and SEM/mediation (H4, H6).

Source: own work based on survey responses.

Figure 2 presents the analytical workflow used to test the integrated TPB–VBN model, guiding the reader through the three sequential stages used to analyze the survey data. The workflow comprises three core models; First, model A uses weighted binary logistic regression (reporting average marginal effects) to predict high investment intention (INT_high) from ATT, SN, PBC, PN, VAL, BEL, CRED, LIT, EXP, and demographic controls. This model addresses RQ4 by identifying which sociopsychological factors best explain intention to invest. Second, model B uses ordered logit/probit regression to predict the investment amount bracket (AMT). The proportional odds assumption is verified using the Brant test. This model examines whether the same factors that drive intention also determine the scale of financial commitment. Third, model C uses mediation analysis (VAL → BEL → PN → INT) with bootstrapping based on 5,000 resamples, supplemented by structural equation modeling (SEM) to validate the integrated TPB–VBN framework. Fit indices (CFI, RMSEA, SRMR) are reported following standard practices (Fornell & Larcker, 1981; MacKinnon et al., 2004; Preacher & Hayes, 2008; Henseler et al., 2015). This model tests the indirect pathway through which values influence intention via beliefs and personal norms (H4–H5).

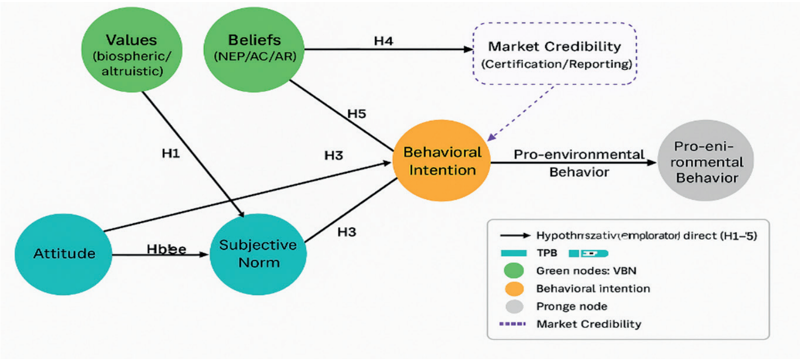

FIGURE 2. Analysis workflow for testing TPB–VBN determinants of green-bond investment (Solid boxes denote required steps; dotted boxes denote optional SEM)

Source: own work based on survey responses.

Robustness, sensitivity, and ethics

We compared weighted versus unweighted estimates, tested alternative link functions (logit/probit), verified proportional odds (AMT), and varied INT thresholds (≥6–7). Additional checks included testing alternative thresholds for INT_high (≥6 and ≥7) and comparing logit versus probit links; results were consistent. Specification checks included adding/dropping CRED, LIT, and EXP. Common-method variance was assessed using Harman's single-factor and a marker-variable approach. All participants gave informed consent. Data were collected anonymously and stored securely. Instruments, coding, and analysis scripts will be made publicly available upon publication.

Results and discussion

Characteristics of the research sample

A total of 387 respondents participated in the survey, distributed across Costa Rica's main provinces with proportional representation (INEC, 2024). The mean age was 36.8 years (SD = 10.2), and 57% identified as male. Approximately 62% reported prior awareness of green bonds, though only 29% had previous sustainable investment experience. All latent constructs (ATT, SN, PBC, VAL, BEL, PN, INT) exceeded reliability thresholds ($\alpha > 0.75$, CR > 0.80, AVE > 0.50). The literacy scale showed relatively low reliability ($\alpha = 0.66$), suggesting cautious interpretation of this variable. Discriminant validity was supported (HTMT < 0.85), confirming adequate measurement properties. Binary logistic regressions show ATT (OR = 1.84, $p < 0.01$) and PN (OR = 2.02, $p < 0.01$) as the strongest predictors of high intention (INT_high ≥ 5/7), with PBC also significant (OR = 1.42, $p < 0.05$), whereas SN was positive but not significant (Table 4).

TABLE 4. Logistic regression predicting high intention (INT_high ≥ 5/7)

Predictor	Odds ratio (OR)	SE	p-value
ATT	1.84	0.31	0.002
SN	1.12	0.27	0.305
PBC	1.42	0.28	0.041
VAL	1.19	0.22	0.118
BEL	1.21	0.25	0.098
PN	2.02	0.36	0.001

*$p < 0.05$; **$p < 0.01$; Nagelkerke $R^2 = 0.38$. This suggests that moral and attitudinal factors dominate over social pressure in shaping investment intention.

Source: own work based on survey responses.

The ordinal regression results predicting investment amount (Table 5) identified PBC ($\beta = 0.29$, $p < 0.05$) as the only robust determinant of scale. This finding suggests that confidence in financial capacity determines how much is invested, while ATT and PN influence willingness rather than allocation.

TABLE 5. Ordinal logistic regression predicting investment amount (AMT)

Predictor	β	SE	p-value
ATT	0.12	0.09	0.201
PBC	0.29	0.11	0.017
PN	0.08	0.07	0.281

$p < 0.05$; pseudo-$R^2 = 0.21$. Thus, perceived behavioral control uniquely determines how much one invests, not just whether one invests.

Source: own work based on survey responses.

Mediation and structural validation

Bootstrapped mediation (Table 6) confirmed a significant indirect effect ($\beta = 0.18$, 95% CI [0.09, 0.28], $p < 0.01$) along the VBN chain (VAL → BEL → PN → INT_high). Values thus shape beliefs, reinforcing moral norms, which in turn drive intention. The direct effect of values remained significant, indicating partial mediation.

TABLE 6. Bootstrap mediation results (VAL → BEL → PN → INT_high)

Effect type	Estimate	95% CI lower	95% CI upper	Significance
Total	0.30	0.18	0.42	***
Direct	0.12	0.01	0.23	*
Indirect	0.18	0.09	0.28	**

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Values exert their influence on intention primarily through the serial mediation of beliefs and personal norms.

Source: own work based on survey responses.

SEM results (Table 7) validated the integrated TPB–VBN model ($\chi^2/df = 2.11$, CFI = 0.95, RMSEA = 0.054). ATT ($\beta = 0.33$, $p < 0.01$), PN ($\beta = 0.39$, $p < 0.01$), and PBC ($\beta = 0.24$, $p < 0.05$) were the strongest predictors of intention, while SN was not significant.

TABLE 7. SEM path coefficients and model fit

Path	Std. β	p-value
ATT → INT	0.33	0.001**
SN → INT	0.08	0.212
PBC → INT	0.24	0.032*
VAL → BEL	0.41	0.000**
BEL → PN	0.37	0.002**
PN → INT	0.39	0.000**

*$p < 0.05$, **$p < 0.01$. R^2 values: INT = 0.46, BEL = 0.17, PN = 0.23. Model fit indices: $\chi^2/df = 1.95$, CFI = 0.95, TLI = 0.94, RMSEA = 0.052, SRMR = 0.047. The integrated TPB-VBN model shows good fit and confirms the dual pathway: attitudes and norms drive intention, while values operate indirectly.

Source: own work based on survey responses.

Hypothesis outcomes

The results confirm TPB's emphasis on attitudes and efficacy (Ajzen, 1991) and VBN's role of values and norms (Dreifert & Rigotti, 2025). Importantly, PBC determined allocation scale rather than intention, suggesting a two-stage decision process: moral and attitudinal drivers generate willingness, while financial self-efficacy shapes magnitude (Li et al., 2023). We propose naming this framework the "dual-path behavioral investment model" to distinguish intention-driven pathways (values/norms) from allocation-driven (PBC) pathways.

Empirically, the Costa Rican case differs from developed markets where institutional trust dominates (Wang et al., 2025). Here, internal values and norms were more decisive, aligning with regional consumer research showing self-efficacy affects the depth of pro-environmental engagement (Okot et al., 2025). For policy, findings stress value-oriented campaigns, transparent regulations, and investor education. PBC can be strengthened through literacy programs, guarantees, and access mechanisms (Khalfaoui et al., 2024). Issuers should communicate how bond proceeds support biodiversity and carbon neutrality goals (Raut et al., 2025). Regionally, similar dual dynamics may apply in other Central American countries; comparative work could assess institutional moderators as markets mature.

Limitations include reliance on self-reported data, projected investment ranges, and omission of trust and corruption variables (Kumar et al., 2025). Future research should use transaction-level data, cross-country designs, and experimental interventions. Overall, green bond investment in Costa Rica is both a moral-normative commitment and a financial efficacy decision, extending TPB–VBN into sustainable finance and offering insights for scaling green markets across Central America.

Theoretical and empirical integration

The results confirm that ATT and PN strongly predict investment intention, consistent with TPB and VBN. The mediation pathway (VAL → BEL → PN → INT_high) further supports VBN. A key distinction emerges: PBC significantly influences the scale of investment, not initial willingness. This two-stage process – values/norms driving willingness, self-efficacy shaping magnitude refines TPB applications in sustainable finance (Li et al., 2023). Situating evidence in Central America, we find that personal values and norms outweigh institutional trust, contrasting with developed markets (Wang et al., 2025). This divergence illustrates how market maturity shapes behavioral determinants. Furthermore, the finding that PBC predicts financial allocation scale aligns with earlier consumer research in Latin America, where self-efficacy shaped the depth of green product adoption (Okot et al., 2025). Extending this to the financial domain highlights that sustainable investment decisions in emerging markets share structural similarities with consumer green behavior.

Policy and market implications

The evidence provides actionable insights into Costa Rica's green finance ecosystem. Policy design should emphasize moral responsibility and ecological values, while market development must strengthen PBC through regulatory clarity, risk guarantees, and accessibility mechanisms (Loiola et al., 2025). Investor education programs targeting self-efficacy can further expand participation (Okot & Castro, 2023; Khalfaoui et al., 2024).

Issuers can also adopt narratives linking green bond proceeds to Costa Rica's environmental goals, such as carbon neutrality and biodiversity protection, reinforcing both attitudinal and normative motivations.

Regional relevance and future research

Although focused on Costa Rica, the results have regional implications. Other Central American countries face similar constraints: high environmental awareness but low financial depth. Panama has launched green finance initiatives (e.g., canal watershed management), while El Salvador and Guatemala remain exploratory (e.g., solar microgrids). The dual mechanism values driving intention, PBC shaping allocation offers a replicable framework for regional policy harmonization. Comparative work could test whether institutional trust becomes more significant as markets mature.

Several limitations warrant acknowledgment. First, self-reported data may introduce social desirability bias. Second, projected investment ranges rather than actual transactions limit precision. Third, institutional variables such as trust in regulators or perceived corruption were omitted, despite their known influence in emerging economies (Kumar et al., 2025). Fourth, dichotomizing investment intention (INT_high ≥5/7) may lose information; future studies could use continuous measures. Future research should adopt longitudinal designs, cross-country comparisons, and experimental interventions to test investor education or risk-reduction policies.

Overall, green bond investment in Costa Rica is driven by attitudes and moral norms, while financial self-efficacy determines investment magnitude. These findings extend TPB and VBN into emerging economies, highlighting that personal and normative motivations dominate where institutional mechanisms are underdeveloped. The results provide theoretical refinement, empirical novelty, and policy guidance for scaling sustainable finance in Costa Rica and beyond.

Conclusions

This study examined the behavioral drivers of green bond investment in Costa Rica using the TPB and VBN frameworks. Results show ATT and PN drive intention, while PBC determines investment scale. This suggests a two-stage process in which values and norms generate willingness, and financial self-efficacy shapes allocation.

Theoretically, the study extends TPB and VBN into sustainable finance in emerging markets, highlighting that normative motivations remain decisive where institutional frameworks are less mature. Empirically, it provides the first systematic evidence from Costa Rica, showing that ecological values and moral norms outweigh institutional trust, contrasting with developed markets where regulation dominates.

Practically, findings indicate the need for interventions that combine normative appeals with financial empowerment. Education campaigns, transparent regulation, and targeted literacy programs can enhance participation, while issuers should align bond narratives with national environmental strategies to strengthen both moral duty and financial confidence.

Regionally, the dual mechanism, identified intention shaped by values and norms, allocation by PBC, offers a replicable framework for Central America, supporting harmonized green finance strategies.

Limitations include reliance on self-reported data and projections rather than actual transactions. Future research should employ longitudinal and comparative designs to validate and expand these findings.

In sum, green bond investment in Costa Rica reflects both economic rationality and moral commitment, moderated by financial confidence. The study offers a foundation for policymakers, issuers, and scholars seeking to scale sustainable finance in Latin America and advance global climate goals. Future research should also explore cross-country comparisons and incorporate institutional trust variables to validate and extend these findings.

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Summary

Behavioral drivers of green bond investment for renewable energy and sustainable infrastructure: a Costa Rican study with Central American implications. This study examines the behavioral drivers of green bond investment in Costa Rica by integrating the theory of planned behavior and the value-belief-norm framework. Using survey data from 387 banked adults and structural equation modeling, we assess how attitudes, norms, values, and perceived behavioral control shape investment intention and allocation toward green bonds, which finance renewable energy systems, sustainable infrastructure, and decarbonization projects. Results show that attitudes and personal norms directly predict intention to invest, while perceived behavioral control determines investment scale. Values indirectly influence intention through beliefs and personal norms. The findings reveal a dual pathway in sustainable finance: normative motivations drive willingness to invest in climate-aligned engineering projects, and financial self-efficacy shapes the level of commitment. As the first systematic behavioral evidence from Costa Rica, this study underscores the importance of investor education, transparent reporting, and literacy programs to mobilize retail capital for green engineering outcomes across Central America.

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Hybrid mangrove-ultrafiltration as an environmental biotechnology innovation for industrial wastewater treatment and reuse in aquaculture

Keywords: environmental biotechnology, biofiltration, mangrove, ultrafiltration, aquaculture

Introduction

Wastewater from the bottled water industry is a significant volume of liquid waste containing suspended solids, organic matter, and microbiological contaminants (Zahoor & Mushtaq, 2023). Although most mineral water plants have wastewater treatment plants (WWTPs), the effluent quality often still fails to meet reuse standards, particularly for sensitive applications such as fish farming (Ruan et al., 2019). Existing WWTP systems tend to rely on conventional, reactive approaches that are costly and difficult to adapt to specific needs (Bergamasco et al., 2011).

Suboptimal WWTP design – whether in filtration media setup, space use, or operational flexibility – frequently fails to achieve the target treated water quality (Loh et al., 2021). There is a need for innovation in wastewater treatment system design that prioritizes not only technical effectiveness but also efficiency, modularity, and adaptability for small- to medium-sized industries (Li et al., 2024).

This study highlights the design and optimization of a hybrid wastewater treatment system that combines biofiltration using mangrove leaf powder with ultrafiltration membrane technology (Ajaz et al., 2024). Unlike conventional approaches that use whole mangrove plants, this study uses dried mangrove leaf powder packed in filtration bags as the initial medium. This form was chosen to address land constraints, prevent clogging, and enhance the absorption efficiency by increasing the contact surface area (Bôto et al., 2023).

Mangrove powder is rich in tannins and polyphenols, which function as active agents for binding heavy metals and organic compounds. This medium also serves as a habitat for degrading microorganisms such as *Bacillus coagulans*, which support biological processes for pollutant removal (Saili et al., 2022). Meanwhile, ultrafiltration serves as the final stage for filtering micro-particles and improving the visual and microbiological quality of water. The semi-designed system developed in this study is intended to produce water quality that meets fish farming standards. The design principles include the following: the use of local materials (mangrove powder), a two-stage modular configuration (biofilter and membrane), and adaptability (Hossain et al., 2022).

Compared with conventional wastewater treatment systems that rely on chemical dosing or advanced mechanical operations, this hybrid design uses passive processes and modular biofilter geometry, offering a low-tech yet scalable alternative (Bergamasco et al., 2011). The urgency of this research lies in the need for a wastewater treatment solution that functions not only as a processing tool but also as an integrated system model ready for replication and application at an industrial scale, thereby preventing pollution and enabling reuse. Furthermore, this system is designed to produce treated water that is not only safe but also suitable for direct reuse in fish farming, thereby supporting integration between wastewater treatment and the fisheries sector.

The objectives of this study were to design a hybrid wastewater treatment system that integrates mangrove leaf powder biofiltration packed in bags with membrane ultrafiltration, to evaluate its effectiveness in improving the quality of bottled drinking water, to assess wastewater quality based on key parameters including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, total dissolved solids (TDS), and dissolved oxygen (DO), and to assess the suitability of the treated water as a medium for fish farming in accordance with aquaculture water quality standards (Roy et al., 2021). This system can promote water efficiency, reduce pollution, and enhance the economic value of wastewater through sustainable reuse.

Material and methods

Aim of the study

This study employs a laboratory-scale experimental approach to simulate the field application of a hybrid wastewater treatment system that integrates mangrove leaf powder biofiltration with ultrafiltration. The system was developed as a prototype and tested with effluent from industrial waste in Lingsar Village, West Lombok. The objective was to evaluate the treatment performance of a hybrid mangrove biofiltration and ultrafiltration system for industrial waste, assessing its suitability for use as water for fish farming. This design has the potential to be replicated in small- to medium-scale industrial environments.

Construction and operation of the hybrid system

The treatment system consisted of two main units:

1. Mangrove leaf powder biofiltration unit. Six sacks of fresh mangrove leaves were dried to produce 1.5 sacks of dried mangrove leaves. One sack (20 kg) of dried mangrove leaves was ground into a fine powder and sieved through a one-millimeter mesh. The powder was then packed into polypropylene sacks measuring 40 × 60 cm, each containing approximately 5–6 l of material. A total of 5–6 sacks were positioned horizontally within a filtration basin measuring 200 × 100 × 75 cm. Wastewater flowed by gravity through the biofilter, with a hydraulic retention time (HRT) of 4 h (Fedorova et al., 2022).
2. Membrane ultrafiltration unit. Effluent from the biofiltration unit was directed into a 10-inch cartridge housing containing three parallel five-micron filter bags. The unit operated in a low-pressure dead-end batch mode, using either

a mini-booster pump or gravity flow. This configuration was chosen for its simplicity, energy efficiency, and adaptability to small-scale industrial applications (Aljahdali & Alhassan, 2020).

Sampling and analysis

Wastewater quality testing was conducted at each stage of the treatment process, including the WWTP influent, the mangrove biofiltration effluent, and the final effluent following ultrafiltration, to assess physical, chemical, and microbiological parameters. Physical parameters included temperature and TSS. Temperature was measured using a calibrated digital thermometer, and TSS, pH, DO, BOD, and COD were also evaluated. pH and DO were measured in situ using a multiparameter water quality meter. BOD was analyzed using a five-day incubation method at 20°C. COD was assessed using a closed-reflux method with a spectrophotometer. Ammonia and phosphate concentrations were determined colorimetrically using standard reagents and a spectrophotometer. Microbiological parameters, including total coliforms and *Escherichia coli*, were analyzed by filtering 250 ml of the sample through low-pressure filter paper, which was then placed on Chromocult coliform agar and incubated for 24 h at 37°C. Detergent testing employed the methylene blue active substances (MBAS) method, which involves reacting the sample with a methylene blue solution in an acidic medium, followed by extraction of the organic phase with chloroform. The resultant blue color intensity was measured using a spectrophotometer and compared against a standard curve. Data were analyzed descriptively to evaluate the effectiveness of each treatment stage and compared with the aquaculture water quality standards (Badan Standardisasi Nasional [BSN], 2008; BSN, 2018; Al Aani et al., 2020).

Results and discussion

The following data illustrate alterations in primary water quality parameters at each phase of the hybrid mangrove-ultrafiltration system. Pollutant concentrations are documented for untreated wastewater, post-mangrove powder biofiltration, and subsequent ultrafiltration. Fluctuations in pollutant load, including DO and pH, demonstrate the efficacy of the treatment process.

TABLE 1. Water quality parameters pre- and post-treatment for aquaculture

Parameter	Average raw wastewater	Average after biofiltration	Average after ultrafiltration	Aquaculture quality standard
BOD [$mg \cdot l^{-1}$]	46.5	22.0	6.1	<10
COD [$mg \cdot l^{-1}$]	130	68.2	19	<50
TSS [$mg \cdot l^{-1}$]	120	36	3.4	<10
DO [$mg \cdot l^{-1}$]	2.3	4.5	6.8	>5
pH [-]	6.4	6.8	7.1	6.5–8.5

Source: own work.

According to Table 1, the hybrid biofiltration and ultrafiltration system with mangrove leaf powder markedly enhanced the quality of mineral water wastewater. BOD, COD, and TSS levels declined, indicating efficient removal of dissolved organic matter. DO levels further evidenced this improvement.

The findings demonstrate that the hybrid system, which integrates mangrove leaf powder biofiltration with membrane ultrafiltration, substantially improves the quality of bottled drinking water wastewater, thereby meeting the standards required for fish farming. This system is explicitly tailored for small- to medium-sized enterprises, with a modular design, low operating pressure, and utilization of cost-effective, locally sourced materials (Jamal-Uddin et al., 2022). The design principles emphasize spatial efficiency and hydraulic adaptability, including maintaining an HRT of 4 h and implementing a screen filter before the ultrafiltration process to mitigate premature fouling (Li et al., 2012).

The reduction in BOD from 46.5 $mg \cdot l^{-1}$ to 6.1 $mg \cdot l^{-1}$ demonstrates the system's effectiveness in physically and biologically reducing dissolved organic matter. This value is below the threshold for freshwater fish farming (Toprak et al., 2022). This efficiency is achieved through a combination of the adsorbent properties of tannins and polyphenols in mangrove leaf powder and the microbial activity of *Bacillus coagulans*, which contributes to biological decomposition. These findings align with studies on horizontal gravel biofilter systems (Rehman et al., 2021), which reported significant reductions in BOD. However, the efficiency observed in this study is higher, likely due to the bag-based configuration, which enables more uniform flow distribution and improved passive aeration.

For COD, there was a decrease from 130 $mg \cdot l^{-1}$ to 19 $mg \cdot l^{-1}$. This indicates the system's ability to remove both easily degradable and more complex-to-degrade organic compounds. The final COD value was well below the standard of above 50 $mg \cdot l^{-1}$ and consistent with a study demonstrating similar efficiency in coagulation-ultrafiltration systems. The results of this study differ from those of a system that relies solely on metal coagulants. This natural-material-based system is more environmentally friendly because it does not leave chemical residues (Kurniawan et al., 2020).

The reduction in TSS from 120 mg·l^{-1} to 3.4 mg·l^{-1} reflects the system's success in filtering both macro- and micro-particles across layers. This reduction shows excellent performance compared with other studies reporting TSS efficiency of ±85% in sand-and-zeolite combination systems (Kumala Sari, n.d.). On the other hand, the system design in this study offers an advantage by utilizing micron-sized powder media packaged in bags, thereby increasing contact area and filtration efficiency (Aini, 2023).

The system shows stable pH between 6.8 and 7.1 and a low final TDS of 320 mg·l^{-1}, indicating adequate chemical stability. This stability is maintained without chemical addition, unlike other systems that use metal coagulants or alkalis for pH adjustment. Moreover, the TDS remains well below the safety threshold of 1,000 mg·l^{-1}.

The difference and advantages of this design compared with other systems lie in its ultrafiltration configuration. The use of a housing filled with a five-micron filter bag has been proven to be efficient at filtering micro-particles. This design is based on the principle of uniform pressure distribution and increased filtration surface area, which can extend the filter's life and reduce backflush requirements. The use of ultrafiltration represents a step forward in the biofiltration process using mangroves (Xu et al., 2022).

The system is additionally equipped with pressure gauges on each tank unit, a feature typically found only in large-scale industrial wastewater treatment facilities. These pressure indicators enable prompt inspection and maintenance, thereby preventing fouling and ensuring consistent HRT (Kawan et al., 2022). Such studies are infrequently reported for approaches utilizing local materials and low-technology methods, thereby underscoring the fact that the innovative aspect of this design resides in its applicability to small- to medium-scale industrial operations (Ahmed & Kareem, 2024). The findings of this study pertain not only to reductions in various pollutants but also to a more practical design approach aligned with the requirements of small- to medium-scale industries. Many prior investigations have only tested the media at a basic laboratory scale. The system developed here is equipped with measurements of operational pressure across all tanks, including biofiltration tanks and ultrafiltration housings. These measurements aim to ensure hydraulic stability and to detect potential blockages or increases in pressure loads at the earliest stage, thereby enabling effective operation in field settings, such as wastewater treatment plants (Kumar et al., 2021).

Aini, Irawansyah, Mentari, I. N., Maulana, A., Salleh, M. N. (2026). Hybrid mangrove-ultrafiltration as an environmental biotechnology innovation for industrial wastewater treatment and reuse in aquaculture. *Sci. Rev. Eng. Env. Sci.*, *35* (3), 292–306. DOI 10.22630/srees.10741

Furthermore, to maintain ultrafiltration efficiency and extend the media's lifespan, the system incorporates a coarse screening filter (mesh approximately 100–200 μm) immediately prior to the ultrafiltration housing inlet. This coarse filter acts as a final safeguard against debris or sizable particles that might bypass biofiltration and potentially lead to fouling or premature clogging of the five-micron filter bag. Although this pragmatic measure is infrequently employed in the small-scale academic research, it holds considerable significance for practical industrial deployment, thereby rendering the system not only technically effective but also practically replicable (Xia et al., 2022).

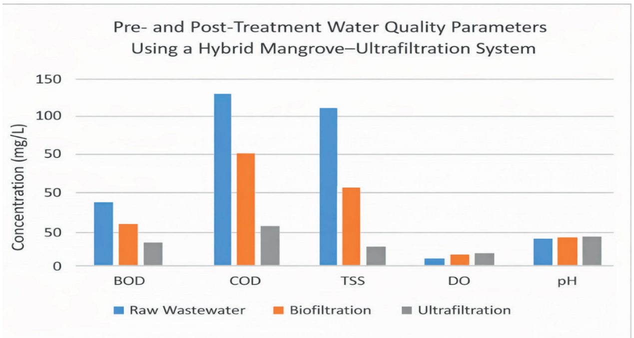

FIGURE 1. Pre- and post-treatment water quality parameters using a hybrid mangrove-ultrafiltration system

Source: own work.

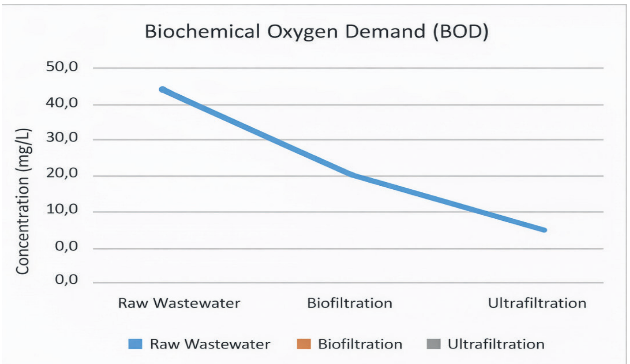

FIGURE 2. Performance of biochemical oxygen demand reduction using mangrove-ultrafiltration system

Source: own work.

The BOD value decreased significantly from 46.5 mg·l^{-1} to 6.1 mg·l^{-1}, demonstrating that the hybrid wastewater treatment system, comprising mangrove leaf powder biofiltration and membrane ultrafiltration, effectively removed organic matter by up to 86.88%. This efficiency is corroborated by the presence of active compounds, such as tannins and polyphenols, which possess adsorbent properties, and by the biological activity of *Bacillus coagulans* within the biofilter. The ultrafiltration process further enhances removal efficacy by removing fine particles and residual compounds. The final BOD value complies with standards for freshwater fish farming (above 10 mg·l^{-1}), making the treated water suitable for use in aquaculture systems (Zhao et al., 2021). In comparison, Fei et al. (2020) achieved 79.2% BOD removal using mangrove powder in batch reactors, indicating that this system attained an 86.88% removal rate under continuous low-pressure flow, reflecting enhanced contact efficiency.

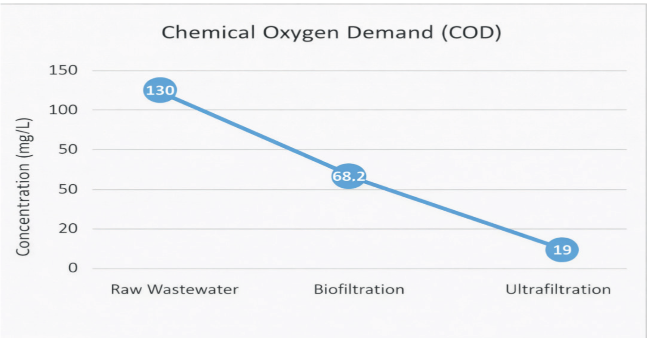

FIGURE 3. Chemical oxygen demand reduction during biofiltration and ultrafiltration processes
Source: own work.

The COD decreased from 130 mg·l^{-1} to 19 mg·l^{-1}, with a removal efficiency of 85.38%, highlighting the effectiveness of the hybrid wastewater treatment system in eliminating complex organic pollutants. During biofiltration, *Rhizophora mucronata* leaf powder serves both as an adsorbent and a microbial substrate. Its removal processes include adsorption of organic compounds via active functional groups, such as tannins and polyphenols, and biological degradation by microbes. The subsequent ultrafiltration stage acts as a physical barrier, removing residual dissolved and colloidal COD fractions post-biofiltration using five-micron filter bags in parallel under low pressure (Mentari et al., 2022).

Aini, Irawansyah, Mentari, I. N., Maulana, A., Salleh, M. N. (2026). Hybrid mangrove-ultrafiltration as an environmental biotechnology innovation for industrial wastewater treatment and reuse in aquaculture. *Sci. Rev. Eng. Env. Sci.*, *35* (3), 292–306. DOI 10.22630/srees.10741

FIGURE 4. Total suspended solids reduction during biofiltration and ultrafiltration processes
Source: own work.

The TSS level decreased markedly from 120 mg·l^{-1} to 3.4 mg·l^{-1}, achieving a removal efficiency of 97.17%. This improvement directly enhances water clarity, a vital parameter in aquaculture (Adjovu et al., 2023). Elevated TSS concentrations can impede light penetration, hinder phytoplankton photosynthesis, and induce gill irritation in fish. In this system, mangrove leaf powder used in the biofiltration stage captures suspended solids through its porous packing matrix, while ultrafiltration effectively removes finer particles (Spence et al., 2023). The resulting clear effluent complies with Indonesian good aquaculture practices (CBIB) and the National Standardization Agency of Indonesia's technical standards (SNI) for freshwater fish culture and supports an aquatic environment conducive to sustainable reuse in aquaculture (Roy et al., 2021).

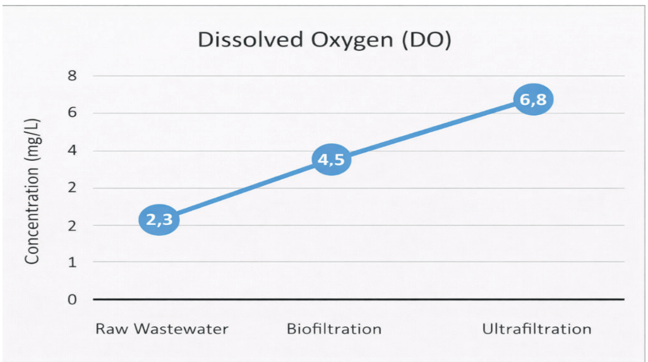

FIGURE 5. Dissolved oxygen during biofiltration and ultrafiltration processes
Source: own work.

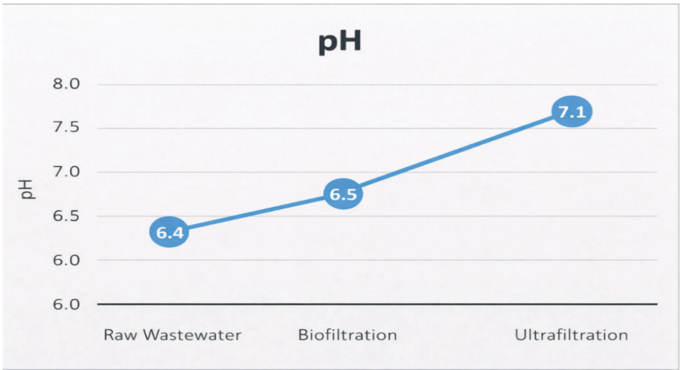

FIGURE 6. Changes in pH at each stage of the treatment process
Source: own work.

The DO concentration increased from 2.3 mg·l^{-1} to 6.8 mg·l^{-1} following biofiltration and ultrafiltration. This enhancement was attributed to the slow vertical flow and interstitial spaces between the filter media, which facilitated passive oxygen diffusion. Notable reductions in BOD and TSS levels also reduced microbial oxygen consumption, thereby increasing DO availability. Aerobic microbial activity within the biofilter further contributed to the development of semi-aerobic conditions, thereby supporting oxygen enrichment. A final DO level exceeding 5 mg·l^{-1} meets aquaculture standards, thereby ensuring optimal conditions for fish respiration, growth, and overall health (Abdulgani et al., 2025).

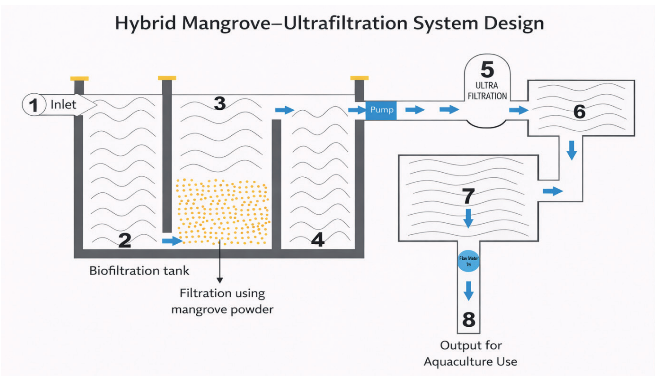

FIGURE 7. Wastewater treatment design with mangroves and ultrafiltration
Source: own work.

Wastewater enters at Point 1 and flows into Tank 2, the initial sedimentation stage. The water then moves to Tank 3, followed by Tank 4, which contains mangrove leaf powder as a biofiltration medium to reduce organic load and contaminants. After biofiltration, the water is pumped into the ultrafiltration unit (Point 5) and filtered through the filter bags in Tank 6 to remove fine suspended particles and residual pollutants. The filtered water then flows to Point 7, the internal outlet. Finally, it exits at Point 8 as treated water that meets quality standards and is suitable for reuse in fish culture or safe discharge into the environment.

The findings of this investigation demonstrate that the hybrid mangrove-ultrafiltration system enhances water quality across all evaluated parameters (Verâne et al., 2020). The BOD decreased by 88%, indicating effective biological degradation and adsorption of organic substances (Zhu & Shin, 2021). Meanwhile, the COD decreased by approximately 85%, reflecting the removal of biodegradable and persistent organic compounds. The removal of TSS reached approximately 97%, underscoring the system's capacity to physically retain fine particles. The DO increased from 2.3 $mg \cdot l^{-1}$ to 6.8 $mg \cdot l^{-1}$, demonstrating the reoxygenation of processed water to levels sufficient to support aquatic life. Elevated dissolved oxygen levels correlate with improved water quality. The pH remained stable within the optimal range of 6.8–7.1, and TDS remained significantly below the permissible limit. These findings affirm the synergistic effect of biofiltration and ultrafiltration processes, supported by natural adsorbents and microbial activity, in producing high-quality effluent suitable for sustainable aquaculture (Abdulgani et al., 2025).

Conclusions

The hybrid wastewater treatment system, integrating mangrove leaf powder biofiltration and membrane ultrafiltration, has demonstrated efficacy in improving effluent quality in the AMDK industry. The system achieved over 85% reductions in BOD, COD, and TSS, while raising DO levels to 6.8 $mg \cdot l^{-1}$, thereby meeting the water quality standards required for freshwater aquaculture. Featuring a two-stage modular design, an HRT of 4 h, and utilizing cost-effective local materials, the system effectively addresses the demand for an efficient IMO-plant WWTP configuration. Furthermore, it confirms that the treated water is suitable for reuse as aquaculture water. This hybrid system offers a novel and scalable engineering solution for decentralized wastewater treatment.

Acknowledgments

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Summary

Hybrid mangrove-ultrafiltration as an environmental biotechnology innovation for industrial wastewater treatment and reuse in aquaculture. This study aims to design and evaluate a hybrid wastewater treatment system that integrates mangrove leaf powder biofiltration with membrane ultrafiltration, an environmental biotechnology innovation, to improve the quality of industrial effluent for reuse as aquaculture media. This study employs a one-group pre- and post-test experimental design. The system comprises a two-stage biofilter unit containing mangrove leaf powder packed in polypropylene sacks, followed by ultrafiltration using three 25-micron filter bags placed in a single housing. Wastewater from the washing process in West Lombok was treated, and water quality parameters – biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), dissolved oxygen (DO), pH, and total dissolved solids (TDS) – were analyzed pre- and post-treatment at each stage. The results showed significant improvements: BOD decreased from 46.5 $mg \cdot l^{-1}$ to 6.1 $mg \cdot l^{-1}$, COD from 130 $mg \cdot l^{-1}$ to 19 $mg \cdot l^{-1}$, and TSS from 120 $mg \cdot l^{-1}$ to 3.4 $mg \cdot l^{-1}$; meanwhile, DO increased from 2.3 $mg \cdot l^{-1}$ to 6.8 $mg \cdot l^{-1}$, and pH stabilized at around 7.1. The effectiveness of this system is supported by the adsorption properties of tannins and polyphenols derived from mangroves as bioremediation agents, as well as by an optimal hydraulic retention time of 4 h. The findings of this research demonstrate that this system is suitable for the sustainable reuse of wastewater in freshwater fish aquaculture.

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Waste management optimization model: toward campus ecofarming based on local food genetic resources for achieving SDG 2 (Zero Hunger)

Keywords: waste management, ecofarming, local food, SDGs 2, circular economy

Introduction

Achieving sustainable development in higher education institutions requires integrated environmental management strategies, particularly in waste management and resource utilization systems. In Indonesia, the Presidential Regulation No. 111

of 2022 on the implementation of sustainable development goals (SDGs) reinforces this national agenda by emphasizing environmental sustainability and community participation. Among current challenges, effective waste management remains critical due to limited facilities, weak partnerships, and low public awareness (Ministry of Environment and Forestry, Indonesia, 2020).

Although the reduce, reuse, and recycle (3R) movement has been promoted for over a decade, awareness of waste segregation and reuse practices remains insufficient (Suryani, 2014). Universities function as experimental environments where sustainable practices, such as waste recycling and ecofarming systems, can be implemented and evaluated. The establishment of integrated waste treatment facilities (IWTFs) on campus supports the 3R principles and operationalizes institutional responsibility in environmental management (Sumarmi et al., 2025). The Ministry of Environment and Forestry Regulation No. 14 of 2021 further provides incentives, such as training, financing, and recognition, for institutions implementing effective waste reduction initiatives.

The Universitas Indonesia Green Metric (2024) assessment identified strategic measures for the State University of Malang (UM), including the development of green open spaces, vertical gardens, biodiversity conservation, and integrated waste management systems. These recommendations align with broader efforts to transform campuses into ecologically resilient spaces through local biodiversity preservation and ecofarming practices (UI Green Metric, 2024).

Ecofarming represents an integrated agroecological approach that links organic waste recycling with local food production systems, enabling circular resource management within institutional environments. This approach contributes to environmental sustainability while supporting food security and local resource independence (Lin, 2022). Universities, as transformative institutions, play a pivotal role in modeling sustainability through education, research, and community service (Yi et al., 2026).

At the State University of Malang (UM), ecofarming initiatives are developed using local food genetic resources, emphasizing tubers, fruits, and other indigenous crops with strong adaptability and nutritional value. These local species, such as cassava, taro, canna, arrowroot, banana, and breadfruit, play a significant role in promoting food sovereignty and reducing reliance on imported products (Jung et al., 2020).

The integration of waste management and ecofarming not only minimizes organic waste but also generates compost and organic fertilizer to sustain agricultural activities. Furthermore, ecofarming serves as a medium for environmental education, reshaping students' ecological awareness (Gupta et al., 2024) and attitudes toward sustainability (Giannini, 2023).

This study addresses the strategic need for developing campus-based ecofarming integrated with waste management. The objectives are to: (1) identify the utilization of organic waste processing results on campus, (2) identify potential local food genetic resources, (3) optimize waste management for ecofarming based on local food potential, and (4) develop an optimization model that supports SDG 2 (Zero Hunger). This study develops an optimization model for waste management toward campus ecofarming based on local food genetic resources to support the achievement of SDG 2 (Zero Hunger). Unlike previous studies that tend to examine waste management, ecofarming, or local food systems in isolation, this research integrates these components into a unified circular system within a higher education context. The proposed model not only connects organic waste processing with sustainable food production but also incorporates local food genetic resources as a core element of system resilience and biodiversity conservation.

By integrating this approach into campus education, research, and participatory activities, this study proposes a framework that positions universities as functional microsystems of the circular economy and agroecological practices. Therefore, this study contributes by broadening the perspective of the circular economy and agroecology at the institutional level, while providing empirical evidence on how integrated campus-based models can effectively support sustainable waste management and local food production.

Literature review

Sustainable organic waste management

Inefficient waste management systems contribute significantly to greenhouse gas emissions, particularly through the decomposition of organic waste in landfills (Son et al., 2025), manifested through climate change (Evans, 2019), rising global temperatures (Wang et al., 2023), ozone depletion (Krupa & Groth, 2023), and the melting of Arctic ice (Schlegel et al., 2023). The rapid reduction of urban green spaces has further exacerbated these conditions by decreasing carbon absorption capacity and intensifying urban heat (Zhang et al., 2024). Green open areas, particularly those integrated with local food cultivation (Münderlein & Bruns, 2025), play a vital role in improving environmental quality and public health (Fadjarajani & As'ari, 2020).

In higher education, integrating composting within campus operations not only reduces greenhouse gas emissions but also serves as a medium of environmental education that strengthens ecological literacy and civic responsibility. Composting converts biodegradable waste into nutrient-rich soil amendments, thereby reducing the need for synthetic fertilizers and supporting sustainable agricultural practices (Nanda & Berruti, 2021). Therefore, waste management in universities must be understood not merely as a technical system but as an educational framework that internalizes sustainability values (Cox et al., 2021; Lucchetta et al., 2025; Gonzalez et al., 2026).

Agroecology and campus ecofarming

Agroecology provides a scientific foundation for sustainable agricultural systems, integrating ecological, social, and economic dimensions (Anderson et al., 2021). In a University setting, ecofarming embodies the application of agroecological principles through practices that link agricultural production with education, research, and community service. Lin (2022) explains that the success of campus ecofarming relies on four interrelated components: environmental education, sustainable agriculture, participatory engagement, and innovation-based research. These elements transform the campus into a living laboratory where sustainability is both practiced and studied (Lin, 2022; Aldogan Eklund, 2026).

Campus ecofarming further supports the green campus vision by combining energy efficiency, carbon reduction, and food production systems based on organic fertilizer derived from institutional waste. Such initiatives link waste management to food resilience and resource efficiency, directly advancing SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) (Hettiarachchi et al., 2020; Ingram, 2023).

Local food biodiversity

Local food genetic resources (LFGR) underpin both food system resilience and cultural sustainability. Overreliance on global staples increases vulnerability to market and climate fluctuations, while indigenous crops, such as cassava, taro, sweet potato, legumes, corn, and banana, offer nutritional diversity and ecological adaptability (Jacob et al., 2023). Integrating these crops into campus ecofarming systems contributes to in situ conservation and sustains agrobiodiversity (Agnoletti & Santoro, 2022; Tacconi et al., 2024).

Ecofarming based on LFGR enhances sustainability by employing native plants resistant to pests and drought, minimizing chemical inputs, and diversifying food sources (Cadena-Zamudio et al., 2024; Suwarno, 2024). By introducing biodiversity into higher education agricultural systems, campuses can educate students about food sovereignty, agrobiodiversity, and local resilience.

Impact on sustainable development goals for achieving SDG 2 (Zero Hunger)

The sustainable development goals (SDGs) provide a universal framework for balancing environmental integrity with social equity. SDG 2 specifically targets hunger eradication, food security, and sustainable agriculture (Food and Agriculture Organization of the United Nations [FAO], 2021). Campus-based ecofarming and waste recycling directly contribute to this agenda by producing food locally, conserving resources, and reducing carbon footprints (Pandey et al., 2025).

A synthesis of previous studies identifies three interconnected pillars of campus sustainability: sustainable waste management, ecofarming systems, and local food biodiversity. Their integration establishes a circular, low-waste model that transforms campuses into micro-laboratories for sustainable development (Debrah et al., 2021; Reijnders, 2024). Meanwhile many implementations remain fragmented due to limited participatory engagement and insufficient local resource utilization (Movilla-Pateiro et al., 2021; Stroparo & Floriani, 2024).

This research advances a holistic framework that unites those three pillars under a participatory and adaptive model, positioning the University as both an academic and ecological actor. Through this integrative perspective, higher education institutions can actively operationalize SDG 2 within localized governance systems and demonstrate measurable contributions to sustainability. The conceptual structure of the proposed innovation is illustrated in Figure 1, which highlights the integration between waste management, local food resource utilization, and their direct contribution to food security and SDG 2 achievement.

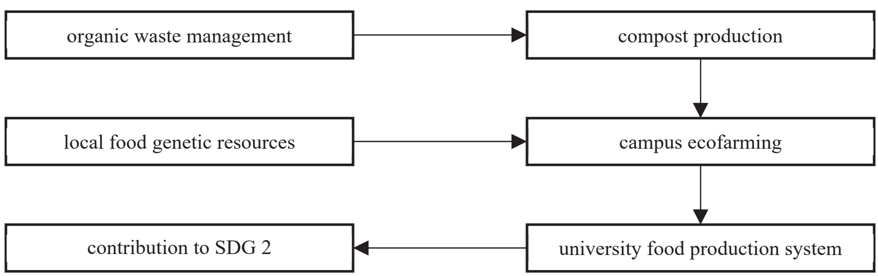

FIGURE 1. Research novelty

Source: own work (2025).

Methods

Research design

This study employed a research and development (R&D) approach utilizing the ADDIE model: analysis, design, development, implementation, and evaluation (Abeysiriwardana et al., 2023). The ADDIE framework was selected for its systematic and iterative nature, allowing the integration of environmental education, media, and waste management processes within educational contexts (Wicaksono, 2024; Maulana et al., 2025). Furthermore, the ADDIE model has structured stages that can be tailored to the needs of the research (Bachri et al., 2024). Methodologically, the ADDIE model has effective stages based on instructional design principles, and all stages allow for accurate assessment (Sumarmi et al., 2024).

The research was conducted at the State University of Malang (UM), East Java, Indonesia, focusing on three primary sites: student cafeterias, organic waste processing units, and integrated ecofarming areas. The study adopted a sequential mixed-method design combining qualitative exploration for model construction and quantitative validation for model effectiveness testing (Zhou, 2019).

The development process followed these five ADDIE stages:

a) Analysis: Conducted through interviews, observations, and focus group discussions (FGDs) with cafeteria managers, gardeners, lecturers, and green campus teams to assess existing waste management practices and identify local food genetic resources;
b) Design: Formulated an integrated ecofarming model combining organic waste recycling, compost production, and local food cultivation layouts;
c) Development: Sorted and processed organic materials through chopping, fermentation, and drying to produce compost and liquid organic fertilizer;
d) Implementation: Applied the model on a pilot scale using compost and fertilizer in campus ecofarming plots under supervision of the green campus and garden divisions;
e) Evaluation: Conducted both formative (during implementation) and summative evaluation (through expert validation) involving specialists in environmental science, agriculture, and education.

Figure 2 illustrates the research and development stages of the integrated waste processing and ecofarming system at the State University of Malang (UM).

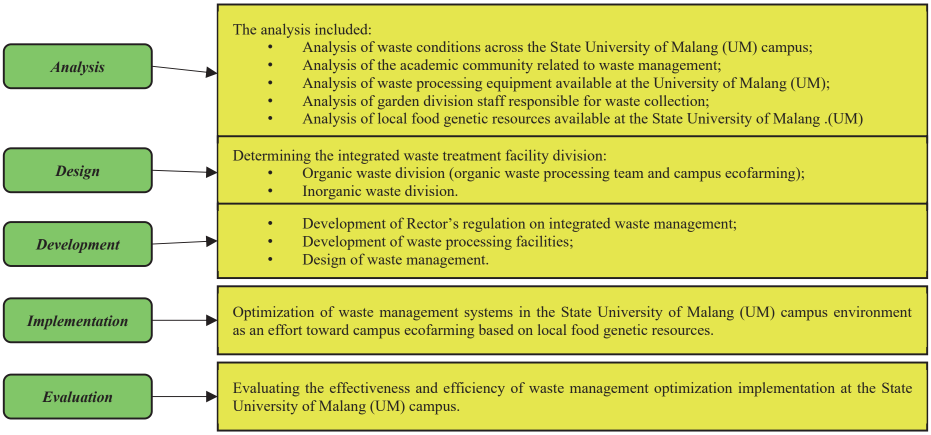

FIGURE 2. Research and development (R&D) stages for integrated waste processing and ecofarming at the State University of Malang (UM)

Source: own work (2025).

Data collecting technique

Data collection was conducted over five working days and was intended to gather data from the integrated waste treatment facility (IWTF), the faculty, and the University. The allotted time for data collection was used to ensure that the data collection process was effective and comprehensive. Four primary data collection methods were employed: observation, interviews, documentation, and field implementation of waste management practices related to ecofarming. The University's IWTF consisted of two divisions: (1) organic waste recycling division, responsible for composting, maggot cultivation, and ecofarming activities; and (2) inorganic waste recycling division, focusing on sorting and repurposing non-organic waste to generate economic value through partnerships with local industries.

Quantitative data included: (1) the number of participating faculties/units, (2) volume of organic waste processed, and (3) ecofarming harvest yields. Purposive sampling served as the basis for selecting interview respondents. The selection of respondents was based on analyzing the organic waste recycling process, the inorganic waste recycling process, and identifying local food genetic resources. Two interview respondents were selected as key informants. Qualitative data derived from interviews with stakeholders regarding challenges, satisfaction, and potential for green entrepreneurship development within the State University of Malang (UM) community.

Data analysis

A mixed-methods analytical approach was applied to achieve a comprehensive understanding of both ecological and social dimensions (Creswell & Clark, 2017). Quantitative data were analyzed descriptively to identify patterns in waste generation, compost utilization, and local food resource development. Qualitative data from interviews and FGDs were analyzed using thematic analysis (Strauss & Corbin, 1998) to conceptualize participatory ecofarming models.

Social data were examined using Miles and Huberman's interactive model involving: (1) data collection, (2) data reduction, (3) data presentation/data display, (4) conclusion drawing and verification, while physical condition data (waste volume, compost yield, and fertilizer output) were processed using percentage tabulation (Miles et al., 2014).

The analysis produced an integrated framework linking organic waste management, compost production, and local food-based ecofarming, forming the empirical foundation for the optimization model described in subsequent sections.

Results and discussion

Utilization of organic waste processing products on campus

The University of Malang (UM) produces around 3 tons of waste every day which comes from cafeteria activities, academic activities, and maintenance of the campus's green open space. Of this amount, around 4,340 kg of organic waste is generated daily, consisting of food waste, green waste, non-hazardous wood waste, and other organic materials. Through the implementation of the IWTF, most of this organic waste is successfully reprocessed through sorting, chopping, fermentation, and drying processes to produce compost and liquid organic fertilizer. Data show that the total amount of organic waste produced each day is 4,340 kg. Of this amount, around 3,133 kg is reused and 459 kg is recycled, resulting in an organic waste utilization rate of around 82%. Data related to the daily total organic waste can be seen in Table 1.

This utilization rate shows that the campus waste management system (Fig. 3) has a relatively high efficiency compared to the national average waste management. According to the Indonesian Ministry of Environment and Forestry, the waste processing rate in Indonesia is still below 40%, while most of the waste still ends up in landfills (Andriani & Atmaja, 2019; Romianingsih, 2023). Thus, the success of processing more than 80% of organic waste in the campus environment shows that an educational institution-based waste management system can be a model of best practice in waste reduction (Merchán-Sanmartín et al., 2022).

TABLE 1. Average daily amount of organic waste managed at the State University of Malang (UM)

Type of organic waste	Amount			
	total [kg]	reused [kg]	up-cycled [kg]	share of the reused and up-cycled [%]
Food waste	375	150	75	60
Green waste	3.250	2.580	250	87
Non-hazardous wood waste	490	256	75	68
Other	225	147	59	91
Total organic waste	4.340	3.133	459	82

Source: own work.

This efficiency also has significant ecological implications. By processing more than 4 tons of organic waste every day, the volume of waste sent to landfills can be substantially reduced. This reduction not only lowers the cost of transporting waste but also reduces the potential for greenhouse gas emissions resulting from the decomposition of organic waste in landfills (Kiehbadroudinezhad et al., 2024). Previous research has shown that composting organic waste can significantly reduce methane emissions compared to conventional disposal methods (Li et al., 2023; Manea et al., 2024). Therefore, the waste treatment system implemented on campus not only improves the efficiency of waste management but also contributes to climate change mitigation and the improvement of the quality of the campus environment (Lee & Lee, 2021; Jakimiuk et al., 2023).

a b

FIGURE 3. Campus waste management system: (a) organic waste shredding; (b) compost fermentation
Source: own field documentation (2025).

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In addition, the existence of 15 temporary landfill points spread across various areas of the campus strengthens the waste sorting system at the source. The location of the temporary disposal site can be seen in Figure 4. This early-stage sorting is an important factor in determining the success of the recycling and composting process because the quality of the organic matter entering the processing facility affects the quality of the compost produced. Thus, the success of organic waste management on campus does not only depend on processing technology but also on the participation of the academic community in consistent waste sorting practices (Ojuri et al., 2024; Sumarmi et al., 2025a).

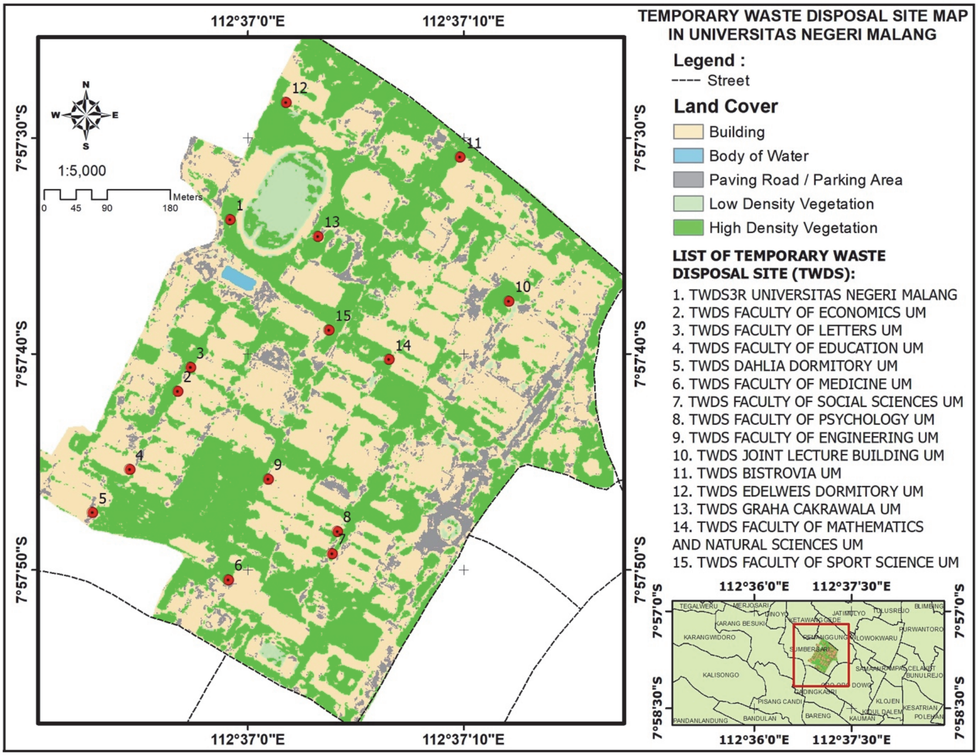

FIGURE 4. Temporary waste disposal sites map at the University of Malang (UM)
Source: own documentation (2025).

The results of the study show that the compost produced from organic waste processing is used directly in campus ecofarming activities. The compost is used as the main fertilizer in various plant cultivation areas spread across several campus open space zones, such as fruit gardens, forest gardens, rare plant collection areas, and food security plots (Zapałowska & Jarecki, 2024). This integration between waste management and agricultural activities creates a circular system where organic waste generated by campus activities is reused as a source of nutrition for local food crops. This approach reflects the principles of a circular economy in resource management, where waste is no longer seen as a final product to be disposed of, but as a resource that can be reused in a sustainable production system. In this context, campus ecofarming serves as a mechanism that connects waste management with local food production and natural resource conservation. Organic compost-based farming systems not only improve soil fertility but also improve soil structure and increase water retention capacity (Blanco-Canqui et al., 2024; Abbasi, 2025).

In addition to ecological benefits, the integration of waste management with ecofarming also provides important educational value for the academic community. Students not only learn the concept of sustainability theoretically but also get directly involved in waste management practices and food production. Thus, campus ecofarming functions as a living laboratory that allows students to understand the relationship between human activities, resource management, and environmental sustainability (Lin, 2022; Nansen, 2024). This approach is in line with the concept of education for sustainable development which emphasizes the importance of experiential learning in shaping environmental awareness and sustainable behavior.

Local food genetic resources available at the University of Malang (UM)

The implementation of ecofarming at the University of Malang (UM) also utilizes local food genetic resources that have high ecological and cultural value. The results of the field identification showed that there were 12 types of local food crops cultivated in the campus ecofarming system, including cassava, taro, sweet potato, canna, arrowroot, banana, breadfruit, jackfruit, pumpkin, and spinach. These plants were chosen because they have high adaptability to local environmental conditions, good nutritional value, and the potential to support food diversification (FAO, 2021; Jacob et al., 2023). Plant diversification is displayed in Figure 5. One form of planting results that has been successful at the University of Malang (UM) shows Figure 6. In addition, the spatial distribution of local food genetic resources in six defined zones, such as fruit orchards, forest gardens, rare plant collections, ornamental gardens, food security plots, and green corridors, is visualized in Figure 7.

a b c d e f

FIGURE 5. Plant diversification: (a) pumpkin plants, (b) tuber plants, (c) cavendish banana plant seedlings, (d) mixed plants of cassava, (e) breadfruit and mangosteen seedlings, (f) mature breadfruit trees
Source: own field documentation (2024).

The ecofarming program integrates twelve local food species, such as cassava, taro, yam, banana, breadfruit, and others, selected for their adaptability, nutritional value, and cultural significance (Fig. 5). Compost and liquid organic fertilizers produced on campus sustain these crops, while hydroponic trials further diversify production. Periodic harvests yield local food products, such as cassava fries and analog rice, supporting food resilience and entrepreneurship.

Harvesting activities conducted every four months, as shown in Figure 6, yield cassava and sweet potatoes that are processed into various food products, such as analog rice, fries, and pastries. These activities contribute to food self-sufficiency, entrepreneurial skill development, and student participation in sustainable agriculture.

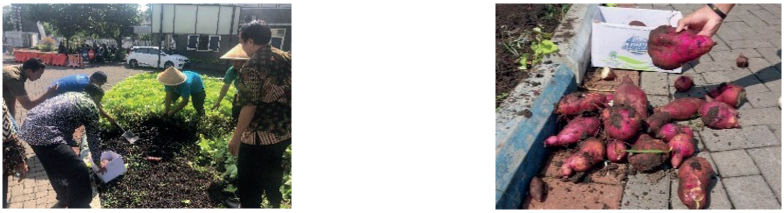

FIGURE 6. Sweet potato harvesting process at the University of Malang (UM)
Source: own field documentation (2024).

The spatial distribution of local food genetic resources across six designated zones, such as fruit gardens, forest parks, rare plant collections, ornamental gardens, food-security plots, and green corridors, is visualized in Figure 7.

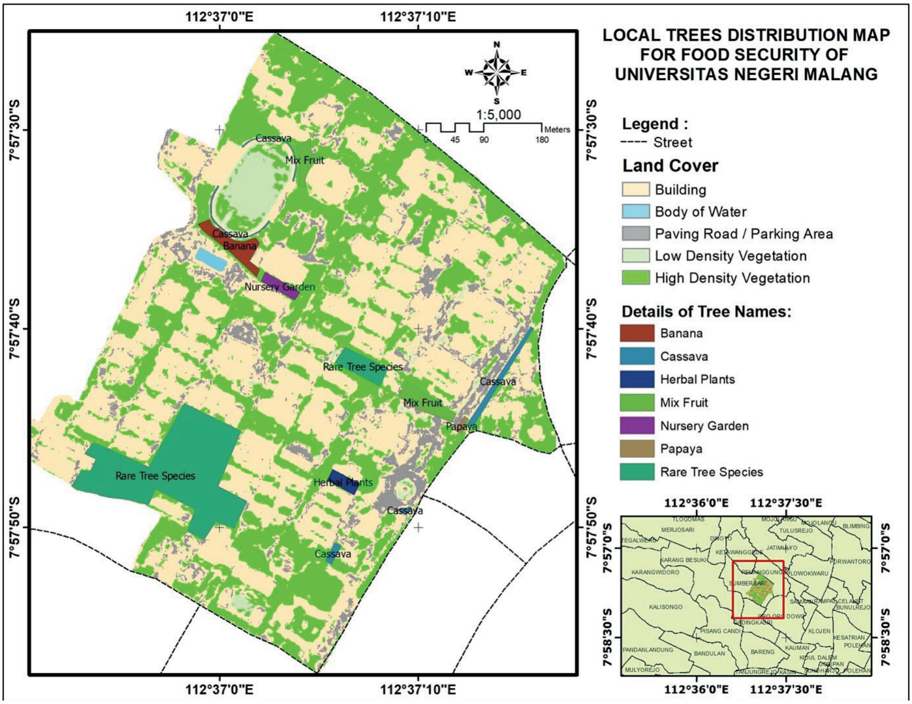

FIGURE 7. Local food genetic resource planting distribution map
Source: own field documentation (2025).

Over-reliance on some global food commodities can increase vulnerability to climate disruptions, price fluctuations, and supply chain disruptions. In contrast, food systems based on local plant diversity tend to be more resilient because they have a wider variety of food sources and better adaptability to environmental changes (Wood et al., 2023; Zuza et al., 2024). The use of local food genetic resources not only supports food production but also plays a role in biodiversity conservation. Local plants cultivated in various open space zones on campus help maintain the sustainability of local germplasm while reintroducing traditional plants to the younger generation. Thus, campus ecofarming functions as an in situ conservation medium for local food crops that have strategic value in a sustainable food system.

Waste management toward campus ecofarming based on local food genetic resources at the State University of Malang (UM)

The integration of waste management and ecofarming forms a circular resource system in which organic waste is transformed into compost and reused to support local food cultivation. Organic waste collected from faculties and cafeterias is shredded, mixed with bio-molasses (biomol), and fermented for approximately one month to produce high-quality compost. Figure 8 illustrates the main stages of this process: collection, shredding, fermentation, and packaging.

a b c d e f

FIGURE 8. Circular resource system: (a) collection of organic waste (leaves) in campus areas, (b) staff conducting the grinding of organic waste, (c) results of the grinding process, (d) biomol production process for compost decomposition bacteria, (e) ground organic waste periodically watered with the biomol solution, and (f) organic compost products ready for use or marketing

Source: own field documentation (2025).

The implementation of waste management models integrated with ecofarming shows a real contribution to the achievement of the SDGs, especially SDG 2 which targets the elimination of hunger, increasing food security, and developing sustainable agriculture. The implementation of waste management toward ecofarming and a campus based on local genetic power can be seen in the contribution of three main aspects. These contributions are reflected in three main areas, namely increasing local food production, diversifying the food system, and strengthening sustainable food literacy in the campus environment.

1. The use of organic compost as the main fertilizer in ecofarming allows for sustainable local food production without reliance on synthetic chemical fertilizers (Zapałowska & Jarecki, 2024). This system not only lowers production costs but also improves soil quality and the sustainability of agricultural ecosystems.
2. The cultivation of various types of local food crops increases the diversification of the food available in the campus environment. This diversification is an important component of a sustainable food system because it can

increase food security against climate change and production disruptions (Cadavid et al., 2024).

3. Ecofarming activities provide students with hands-on experience in sustainable food production practices. Students are involved in various activities, such as planting, plant maintenance, and harvesting and processing of agricultural products. This engagement strengthens students' understanding of the importance of local food systems and environmental sustainability.

Thus, campus ecofarming not only functions as a food production system but also as an educational platform that integrates resource management, environmental conservation, and food security. This model shows that higher education institutions can play a strategic role in supporting the achievement of sustainable development goals through integration between research, education, and sustainability practices at the institutional level. This path is also supported by being inaugurated in the Rector's Regulation on integrated waste management, which is embedded in the green campus roadmap of the State University of Malang (UM) (Fig. 9).

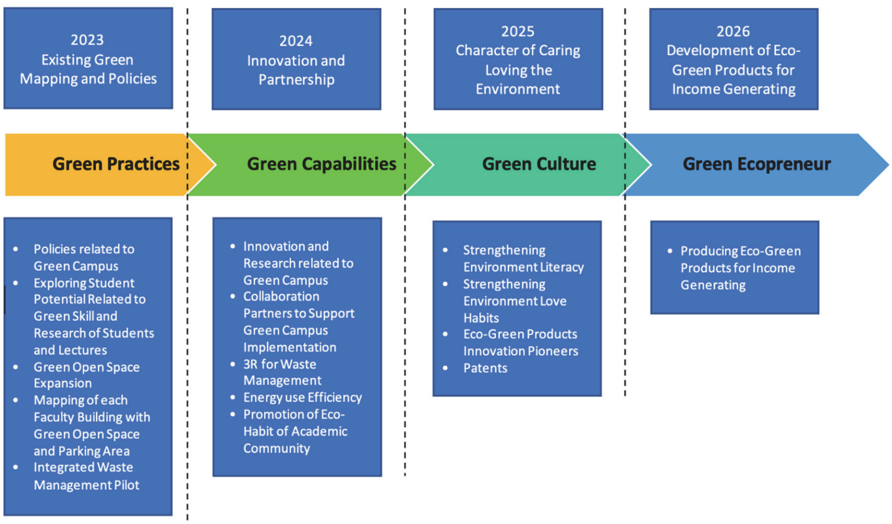

FIGURE 9. Green campus roadmap of the State University of Malang (UM) in sustainable environmental management

Source: own work (2025).

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Waste management optimization model toward campus ecofarming based on local food genetic resources to support SDG 2 (Zero Hunger) achievement

The synthesis of research findings shows that the integration of organic waste management with campus ecofarming forms a circular system that optimizes the use of resources while supporting sustainable food production. This model connects four main components, namely the separation of organic waste at the source, the production of organic compost and fertilizer, the use of compost for the cultivation of local food crops, and the integration of these activities in the campus education and research system. The integration creates a feedback mechanism that allows organic waste generated from campus activities to be reprocessed into productive inputs for the ecofarming system, thereby reducing the volume of waste while increasing the efficiency of environmental resource utilization.

From a sustainability system perspective, this model shows that waste management serves not only as a waste reduction strategy but also as a source of input for local food production. The compost produced from the organic waste processing process increases soil fertility and supports the growth of local food crops, such as cassava, taro, sweet potatoes, and bananas which have high ecological adaptability. The diversification of these crops strengthens local food security while supporting the conservation of food genetic resources. Thus, campus ecofarming not only contributes to waste reduction but also builds a resilient and sustainable local food system.

In addition to the ecological benefits, this model also has important social and educational dimensions. This approach shows that higher education institutions can play a strategic role in supporting the achievement of SDG 2 (Zero Hunger) through strengthening local food systems, diversifying food crops, and developing sustainable agricultural practices based on local resources. The following model strengthens the waste management optimization system for ecofarming. To strengthen the system analysis, the relationship between the components of waste management and ecofarming can be modeled as a simple optimization system, as shown in the following formula:

$$\max Z = C + F - W$$

where: Z – optimal value of waste management system, C – amount of compost produced, F – local food production from ecofarming, W – amount of untreated organic waste.

This model can be interpreted if the optimal system is achieved when compost and food production increases, while the amount of untreated waste decreases. The synthesis of findings produced a waste management optimization model, illustrated in Figure 10, which connects organic waste management, compost production, local food cultivation, and education. The model emphasizes a circular process where waste serves as an input for ecofarming, and the ecofarming outputs strengthen food resilience and learning outcomes.

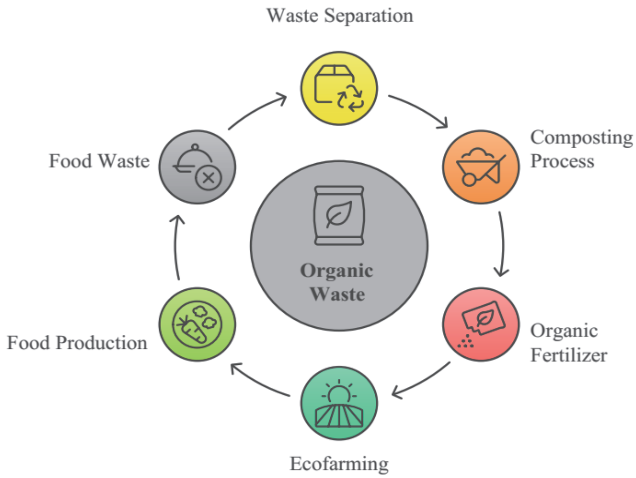

FIGURE 10. Waste management optimization model toward campus ecofarming based on local food genetic resources

Source: own work (2025).

The model comprises four integrated elements: (1) organic waste reduction and segregation at the source (Erälinna & Szymoniuk, 2021); (2) compost and liquid fertilizer production from organic waste (Tittonell et al., 2022); (3) utilization of compost for cultivating local food crops, such as taro, cassava, and breadfruit (McKay et al., 2025); and (4) cross-disciplinary integration of education and research (Lin, 2022). These components form a continuous feedback system that minimizes waste and maximizes ecological benefits.

The circular system model illustrated in Figure 10 shows that campus-based organic waste management can serve as an integrative mechanism that connects waste management systems with sustainable food production. Through the stages of waste sorting, composting, use of organic fertilizers, and the implementation of ecofarming, organic waste is converted into productive resources that support local food production. This system creates a feedback cycle where food waste generated from consumption activities is re-entered into the waste management system to be processed into compost, thus forming a circular economy mechanism that minimizes waste and maximizes resource efficiency (Arthur et al., 2022; Cadavid et al., 2024).

This model shows that the integration between organic waste management and ecofarming not only produces ecological benefits in the form of waste reduction and increased soil fertility, but also contributes to local food security through food production based on local genetic resources. This approach strengthens the concept of campus sustainability system, where higher education institutions function as living laboratories that integrate environmental management, food production, and sustainability learning in one systemic framework. Thus, this optimization model makes an empirical contribution to the literature on circular waste management and campus agroecology, and shows that educational institution-based ecofarming can be an effective strategy to support the achievement of SDG 2 (Zero Hunger) through strengthening a sustainable, efficient, and participatory local food system.

In addition to making an empirical contribution to sustainable waste management practices in the university environment, this optimization model also has important theoretical and policy implications for the development of sustainable campus system. Theoretically, this model expands on agroecological and circular economy approaches by showing how the integration of organic waste management and local food production can form resilient microfood systems at the institutional level. From a policy perspective, the results of this study show that the development of integrated waste treatment facilities that are integrated with ecofarming activities can be an effective strategy for universities in improving the efficiency of waste management while supporting local food security. In addition, the systemic approach developed in this study has the potential to be replicated in a variety of other higher education institutions, especially those with open space resources and significant organic waste production. Thus, this model is not only relevant in the local context of the State University of Malang (UM) but also offers an adaptable conceptual framework to strengthen sustainability practices and the implementation of sustainable development goals on various campuses at the national and global levels.

Conclusions

The developed optimization model for waste management toward campus ecofarming based on local food genetic resources demonstrates that environmental sustainability can be achieved through integrated and participatory systems. The model has been successfully implemented at the State University of Malang (UM) and proven effective in reducing waste, producing compost and liquid fertilizer, and utilizing them for cultivating local food crops.

The integration of waste management with ecofarming activities contributes directly to the achievement of SDG 2 (Zero Hunger) by supporting food independence, biodiversity conservation, and sustainable agriculture. It also creates educational benefits through students' involvement in waste processing, planting, and harvesting activities, which strengthen their environmental awareness and responsibility.

The developed model links four key components: waste reduction and segregation, compost and fertilizer production, utilization for local food cultivation, and academic integration through education and research. This system reflects a circular and sustainable approach that transforms waste into valuable resources, while enhancing ecological and social resilience within the campus community.

The proposed model offers a structured framework for integrating organic waste processing, compost production, and local food cultivation within university sustainability programs. The results affirm that campuses can act as living laboratories for sustainability by combining scientific innovation, education, and community participation in a single operational model.

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Data availability

Research data supporting the findings of this study are available from the corresponding author upon reasonable academic request.

Competing interests declaration

The authors certify that no competing financial interests or personal relationships exist that could potentially have influenced the research outcomes reported herein. This research was reviewed by the Ethics Committee of the University of Malang (Universitas Negeri Malang), which confirmed that the study was exempt from ethical approval under Institutional Review Board Statement letter number 13.3.5/UN32.14/PB/2026.

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Summary

Waste management optimization model: toward campus ecofarming based on local food genetic resources for achieving SDG 2 (Zero Hunger). This study develops an optimization model for waste management toward campus ecofarming based

on local food genetic resources to support the achievement of SDG 2 (Zero Hunger) at the State University of Malang (UM). This study utilizes the research and development (R&D) method with the ADDIE model and a mixed-methods approach. The campus processes approximately 4,340 kg of organic waste daily, of which 3,133 kg is reused and 459 kg is reprocessed, achieving a utilization rate of 82%. Through a systematic sorting process at 15 temporary disposal sites, organic waste is converted into compost through a one-month fermentation process using bio-molasses. The compost is utilized for cultivating 12 local food species – tubers (taro, cassava, sweet potato, yam), fruits (banana, breadfruit, jackfruit), and vegetables (pumpkin, moringa, spinach, corn). The model encompasses four interrelated components: (1) waste reduction and segregation at source; (2) compost and organic fertilizer production; (3) utilization for local food cultivation; and (4) interdisciplinary educational and research integration. Implementation reduces waste volume, promotes biodiversity conservation, enhances environmental awareness, and contributes to food security through sustainable local food systems. This study provides an integrative framework for implementing circular waste management systems in higher education and demonstrates how campus-based ecofarming can support sustainable food systems and SDGs.

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Experimental treatment of oil-contaminated soil structure using vermiculture

Keywords: petroleum-contaminated soil, soil bioremediation, zooremediation, vermiremediation, *Eisenia fetida*, *Lumbricus terrestris*, vermiculture, vermicompost, total petroleum hydrocarbons, TPH, polycyclic aromatic hydrocarbons, PAH, carbon-to-nitrogen ratio, C : N, hydrocarbon degradation, microbiological activity, organic amendments, oil sludge, Atyrau Region, Kazakhstan

Introduction

The Atyrau Region, situated in western Kazakhstan within the Caspian Depression, constitutes the historical and contemporary center of the country's petroleum industry. The region hosts two of the world's largest hydrocarbon deposits – Tengiz and Kashagan – alongside the Atyrau Oil Refinery (AORZ), a subsidiary of the national company KazMunayGas, which has been in continuous operation since the Soviet Union. Environmental monitoring data indicate that approximately 59% of total soil contamination attributable to the oil industry across Kazakhstan is concentrated in the Atyrau Region (Funtikova et al., 2023). The total area of oil-contaminated land in western Kazakhstan exceeds 194,000 ha, with the volume of spilled petroleum estimated at over 5 million tons. Hydrocarbon concentrations in soils frequently exceed permissible levels by factors of 5–10, while heavy metals – including lead, cobalt, nickel, cadmium, copper, zinc, vanadium, and molybdenum – occur at concentrations 2–12 times above regulatory thresholds (Koshim et al., 2022). Groundwater contamination near petrochemical facilities further reflects this burden, with petroleum hydrocarbons exceeding standards fourfold, chlorides ninefold, and sodium sixfold (Radelyuk et al., 2020). A particularly acute environmental risk is associated with the evaporation ponds and sludge impoundments of the Atyrau Oil Refinery, covering approximately 860 ha and located near residential areas, thereby posing direct risks to groundwater and air quality for a population of nearly 300,000 (European Bank for Reconstruction and Development [EBRD], 2021).

Petroleum sludge represents a complex and hazardous waste composed of crude oil residues, emulsified water, mineral particles, and toxic compounds, including polycyclic aromatic hydrocarbons (PAHs) and monoaromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Total petroleum hydrocarbons (TPH) are among the most widespread persistent organic pollutants in industrial environments and exhibit toxicity across multiple trophic levels (Koolivand et al., 2020). The cumulative volume of oil sludge stockpiled across Kazakhstan is estimated at approximately 40 million tons (Boiko et al., 2023), with a significant proportion concentrated in the Atyrau Region. These wastes are typically stored in unlined or poorly sealed sites, where high salinity, oxygen limitation, and intrinsic toxicity severely constrain natural attenuation processes, extending remediation timelines to decades (Nobili et al., 2022).

Against this background of large-scale contamination, vermiculture has emerged as a promising biotechnological approach for the remediation of hydrocarbon-polluted soils. Vermiculture employs earthworms to transform and detoxify organic substrates, facilitating pollutant degradation through improved aeration, stimulation of microbial activity, increased bioavailability of hydrocarbons via bioturbation, and enzymatic processes occurring within the earthworm digestive system (Dada et al., 2021). This approach is particularly attractive due to its low cost, environmental compatibility, and capacity for in situ application under field conditions.

The central mechanism underlying vermiremediation is the synergistic interaction between earthworms and soil microorganisms. Earthworms physically fragment and redistribute contaminated substrates, creating microaerophilic niches and enhancing oxygen diffusion, while their gut-associated microbiota interacts with indigenous hydrocarbon-degrading bacteria. This earthworm–microbe synergism facilitates the biochemical breakdown of hydrocarbon chains and significantly enhances degradation efficiency compared to isolated biological processes. This interaction represents the key functional basis of vermiculture-based remediation systems.

Beyond remediation applications, vermicompost has also been extensively documented as an effective soil amendment for crop production, with meta-analyses reporting significant increases in nutrient availability and yield across diverse agricultural systems (Blouin et al., 2019; Hanc et al., 2022; Ma et al., 2022; Alinouri et al., 2024; Bai et al., 2024; Mohite et al., 2024; Sande et al., 2024). These findings highlight the dual ecological and agronomic potential of vermiculture technologies, linking soil remediation with restoration of soil fertility and productivity.

However, in the context of petroleum-contaminated soils, achieving conditions suitable for biological remediation remains a critical challenge. Mechanical approaches, such as soil mixing and dilution with clean substrates, are commonly used to reduce hydrocarbon concentrations. These methods redistribute contaminants, promote volatilization of lighter fractions, and reduce surface concentrations. Nevertheless, even after such treatment, residual hydrocarbon levels often remain high (e.g., about 10 $g \cdot kg^{-2}$), limiting the applicability of biological remediation techniques.

As demonstrated by Tauova et al. (2023), effective reduction of hydrocarbon concentrations through mechanical means requires the addition of large volumes of uncontaminated material and repeated mixing cycles. For example, halving contamination levels may require the application of clean substrate layers up to 0.7–0.8 m thick, followed by continuous mechanical disturbance. Such approaches are often impractical at large spatial scales due to the limited availability of clean materials and high operational costs. Moreover, single-stage treatments are typically insufficient to restore soil structure or activate biological processes necessary for sustainable remediation.

These limitations necessitate the development of integrated approaches that combine physical and biological processes. In this context, earthworms represent a promising biotechnical solution, functioning as continuous, self-sustaining agents of soil mixing and structural restoration. Through burrowing activity, earthworms create stable channels that enhance oxygen penetration into deeper soil layers, while their movement promotes redistribution of soil particles and prevents compaction. The passage of soil through the digestive system contributes to the formation of granular structure and increases the contact surface between soil and air, thereby facilitating microbial degradation processes.

Particularly important in this regard are species such as *Eisenia fetida* and *Lumbricus terrestris*, which exhibit relatively high tolerance to hydrocarbon-contaminated environments. Their activity not only enhances soil aeration and structure but also contributes to changes in soil chemical properties, including increased alkalinity due to calcium carbonate excretion. Additionally, earthworms play a role in nutrient cycling by accelerating the biochemical decomposition of organic matter, thereby enriching soils with bioavailable mineral components.

In light of these considerations, the present study investigates the potential of vermiculture-based bioremediation of petroleum-contaminated soils in Kazakhstan, with a specific focus on the ecological and functional roles of *Eisenia fetida* and *Lumbricus terrestris* under conditions of hydrocarbon stress. By examining the interactions between earthworms, soil structure, and contaminant dynamics, this work aims to provide experimental evidence supporting the development of sustainable and scalable remediation strategies for oil-impacted environments.

Material and methods

The research work was carried out in the spring of 2025 with soil samples taken from the Tengiz field of the Republic of Kazakhstan, the Atyrau Region. Laboratory experiments were carried out in the complex geotechnical Laboratory of JSC NIPI Caspian Oil and Gas. Two different earthworms were used for the experiment:

– *Eisenia fetida* (Californian red worm) is a species adapted to composting, often used in petroleum research.

– Native wild earthworms (*Lumbricus terrestris*, *Drawida* spp.): endogean species found in the natural conditions of Kazakhstan.

The worms underwent acclimatization in a standard organic environment for 7 days before the experiment. As an organic environment necessary for the life of worms rotted manure (cow), crushed straw and biohumus (compost) was used. The mixtures were mixed with the soil in a 3 : 1 ratio and kept at a moisture level of 65–70%.

After the introduction of worms, the samples were monitored for 90 days. The soil moisture was checked once a week and, if necessary, sprayed with water. The temperature was maintained in the range of 22–25°C.

Every 30 days (0, 30, 60, 90 days) the following parameters were determined:
– Total petroleum hydrocarbons (TPC) by Soxhlet extraction and IR spectroscopy.
– pH and electrical conductivity – standard 1 : 2.5 through soil–water suspension.
– Organic matter-detected by the furnace method (loss on ignition – LOI).
– Biomass and number of worms by counting and measuring manually.
– Microbiological activity-dehydrogenase enzyme activity (TTC test).
– Phytotoxic test-on wheat seed germination.

The results were processed using Microsoft Excel and SPSS programs. Statistical differences were detected using a single-factor variance analysis (ANOVA) and the Tukey HSD test. Reliability level at $p < 0.05$.

The study used two types of untreated organic waste, such as food waste (eggshells, fruits and vegetables) and garden waste (plant residues). Before composting, all waste is crushed and sieved for more efficient decomposition by worms. After various organic materials were obtained, three different types of compost piles were prepared, which were placed in special containers. During the preparation of each pile, various organic raw materials (fruits, vegetables, and eggshells) were mixed in certain proportions (180 g per kg) and carefully mixed with fillers (plant residues, tree clippings, and sawdust) to ensure a C : N ratio (the total gram of organic raw materials was 180 g per test) necessary for effective decompositions (Table 1). To estimate the carbon and nitrogen content in each waste component, composition data was applied (Table 1) and then used to calculate the total carbon and nitrogen content in the waste mixture. The C : N calculation was performed for each type of waste based on the mass and composition of the components in the ratio of 180 g of waste (Ducasse et al., 2022).

TABLE 1. Composition of organic material and C : N ratio of each compost

Pile	Compost composition	Weight (g/per test) [%]	Carbon (C) [%]	Nitrogen (N) [%]	C : N ratio [g]
A	(70 wt% mixed fruits and vegetables + + 30 wt% vegetable residues)	180	48.5 (27%)	1.3 (0.7%)	37.3
B	(50 wt% vegetable residues + 25 wt% eggshells + + 25 wt% mixed vegetables and fruits)	180	46.2 (25.7%)	1.4 (0.8%)	33.0
C	(50 wt% eggshell + 40 wt% vegetable residues + + 10 wt% mixed fruits and vegetables)	180	47.4 (26.3%)	1.5 (0.8%)	31.6
D	(70 wt% mixed fruits and vegetables + + 30 wt% vegetable residues)	180	48.0 (26.7%)	1.2 (0.7%)	40.0

wt% – mass fraction.

Source: own work.

Californian red worms and wild earthworms as a biological factor of soil formation. The study used Californian red worms, also known as "red worms" (*Eisenia fetida*), and wild earthworms (*Lumbricus terrestris*). Californian red worms and earthworms (Pile A, Pile B, Pile C) were used in three composts (Pile D). This was planned to compare their individual species ability to biodegrade organic materials, compare the rate of decomposition of waste [g·day^{-2}] of two varieties of worms, and evaluate their potential to improve the structure of the soil as a vegetable fertility. By making numerous passages and burrows, they improve the physical properties of the soil: they increase its porosity, aeration, moisture capacity and water permeability. In soils enriched with earthworm waste products, coprolites, the amount of humus increases significantly, the amount of exchange bases increases, and soil acidity decreases. Soils containing worm coprolites also have a more water-resistant structure. Table 2 illustrates the features and differences between these two types of worms (Domínguez & Edwards, 2011).

TABLE 2. Comparison of Californian red worms and wild earthworms

Indicator	Californian red worm (*Eisenia fetida*)	Wild earthworm (*Lumbricus terrestris*)
Life span	10–16 years old	Up to 10 years old
Adapting to a new place	Relatively fast	Slowly getting used to the composter
Feed change	They cross with difficulty	At first, they refuse to eat
Types of feed	Any waste of plant origin	Waste found in the natural environment
Acceptable temperature	0–40°C	0–30°C
Assiduity	Good	Average
Reproduction	Every 5–7 days	For a long time, as in nature – 4–6 times a year, mainly in spring and early summer
Body length	80–100 mm	60–130 mm

Source: own work.

Organic waste was composted in containers (50 cm high, 50 cm wide, and 70 cm long), which were periodically turned over with the use of an aeration device providing sufficient oxygen and accelerated decomposition. Humidity was maintained at about 50%, which created optimal conditions for composting (Castillo et al., 2011). The process lasted 12 weeks, which was confirmed by monitoring the chemical, biological, and physical properties and comparing them with international standards for finished compost. The temperature in the containers and the environment was measured daily using a thermometer and measurements were carried out at different levels of the container, at a depth of 30–40 cm. To assess the rate of decomposition of waste in each container, a periodic analysis of the residual material was carried out every 5 days for 1.5 months (40 days). The analysis included the determination of the mass of the remaining unprocessed waste and changes in their physico-chemical characteristics. An amount of 180 g of waste was initially added to each container, and three independent tests were performed for each type of compost (Pile A, Pile B, Pile C, Pile D) to increase the reliability of the results obtained (Gajalakshmi & Abbasi, 2008).

The data obtained on the dynamics of decomposition were used to compare the efficiency of the process depending on the type of worms used (Californian red worms or wild earthworms) and the composition of the compost. The average decomposition rate was calculated every 5 days using the following formulas (Edwards et al., 2010):

$$S_{\text{cp}} = \frac{M_0 - M_t}{t}$$

where: S_{cp} is the average decomposition rate [g·day^{-2}], M_0 is the initial mass of waste [g], M_t is the mass of waste at a time [g], t is the duration of decomposition [day].

The research and analysis of the final result of composting were carried out at the SWAPTEL Laboratory for Soil, Water, and Plant Analysis in the Atyrau Region (Khalel Dosmukhamedov Atyrau University) (Fig. 1). Each compost (Pile A, Pile B, Pile C, and Pile D) was subjected to a comprehensive analysis, including an assessment of chemical, biological, and physical properties such as pH, nutrient content [nitrogen (N), potassium (K_2O), and phosphorus (P_2O_5)], as well as the dynamics of changes the mass and number of worms in each container. Samples for analysis were taken at different stages of composting and at the end of the process. Each sample was a mixture of sub-samples taken from different points in the container and sent to the laboratory for analysis (Tauova et al., 2022).

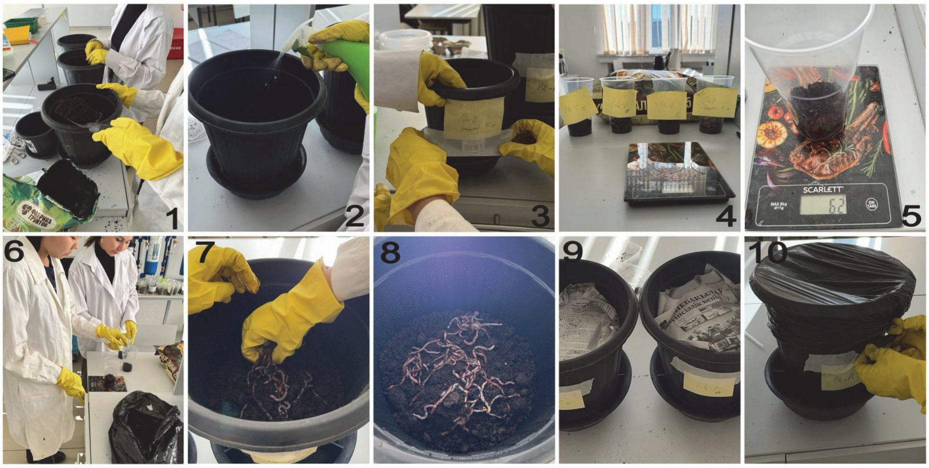

FIGURE 1. Analysis of the final results of composting
Source: own work.

The number and biomass of earthworms were considered as one of the key bioindicators of oil-contaminated soil restoration. At the initial stage of the experiment (day 0), all experimental variants were characterized by the same conditions: the average number of worms was 50 individuals per container, with a total biomass of 60–65 g. The presence of petroleum hydrocarbons had a stressful effect on soil biota, which manifested itself in reduced activity and delayed physiological processes in worms during the first 10–15 days of the experiment. At the end of the 90-day observation period, a statistically significant increase in the population size to 62–65 individuals was recorded in the variants using *Eisenia fetida*; an increase in biomass to 85–90 g was also recorded. The weight gain averaged 40–45%, which indicates the high resistance of this species to the toxic effects of oil and its ability to adapt to changing environmental conditions. In the variants with native wild earthworms (*Lumbricus terrestris*), the increase in abundance and biomass was less pronounced: the number of individuals increased to 52–55, and the biomass increased to 50–55 g. Nevertheless, even at lower rates, stabilization of the worms' physiological state and preservation of their viability were noted, which indicates the potential for their participation in the processes of zooremediation with a longer exposure period. The results obtained confirm that the increase in the number of earthworms directly correlates with a decrease in the toxicity of the soil environment, improved aeration, and activation of microbiological processes involved in the biodegradation of petroleum hydrocarbons.

Results

In the course of the study, the effectiveness of cleaning oil-contaminated soil as a result of worms was analyzed by various methods, including vermiculture. The presented results cover key aspects of the process, such as the rate of waste decomposition, the dynamics of the mass and number of worms, temperature and pH profiles, as well as changes in the composition of the main macronutrients (nitrogen, phosphorus, potassium). The analysis of the obtained data makes it possible to determine such influencing factors as the composition of the source material, the ratio of carbon to nitrogen (C : N), microbiological activity, and conditions of detention. The results provide a detailed understanding of decay processes (Angie et al., 2021).

Figure 2 shows the average decomposition rate of four types of food waste (Pile A, Pile B, Pile C, Pile D) in worm feeding [g·day^{-2}], the measurement interval is indicated every 5 days for 40 days. Pile A (70% fruits and vegetables, 30% vegetable waste) showed a maximum decomposition rate of 10.45–27.84 g per day, due to its high biodegradability and the optimal C : N ratio of about 37.3. Pile B (50% vegetable waste, 25% eggshells, 25% fruits and vegetables) increased from 7.0 g·day^{-2} to 23.77 g·day^{-2}, although the growth rate slowed after the 25th day due to high calcium content and depletion of easily accessible substances. Pile C (50% eggshells, 40% vegetable waste, 10% fruits and vegetables) showed an average result, this indicator increased from 6.3 g·day^{-2} to 13.73 g·day^{-2}, slowed down due to complex carbon components and C : N equal to 31.6. The earthworm-containing Pile D (70% of fruits and vegetables, 30% of plant residues) reached only 10.43 g per day, which is lower than the Pile A of Californian earthworms (27.84 g·day^{-2}); this indicates the low efficiency of earthworms. The carbon content is high. Thus, waste using optimal C : N and Californian red worms (Pile A, Pile B) decomposes faster, while Pile C and Pile D require additional measures to speed up the processes (Lalander et al., 2015).

Figure 3 shows the change in the mass and abundance of worms under different conditions of the composition and composition of organic waste. Californian red worms (Pile A, Pile B, Pile C) have shown a significant increase in mass and abundance, which indicates their high adaptability and efficiency in the conditions of decomposition of organic materials. In particular, the mass of worms in the pile increased from 62 g to 87 g, and their number increased from 50 individuals to 63 individuals, which corresponds to the largest increase among all species. Wild earthworms (Pile D), on the other hand, showed less pronounced

Tauova, N., Berzhanova, M., Saburova, N., Izimova, R., Nurmukhanova, G., Nurbayeva, F., Jumasheva, K. (2026). Experimental treatment of oil-contaminated soil structure using vermiculture. *Sci. Rev. Eng. Env. Sci.*, *35* (3), 333–351. DOI 10.22630/srees.11008

changes when their weight increased from 45 g to 52 g and their number increased from 50 to 53. This indicates that this type of worms has a limited ability to process the organic waste presented under the indicated conditions. The presented data show differences in the efficiency of processing soil contaminated with oil by Californian red worms and wild earthworms (Chaher et al., 2020).

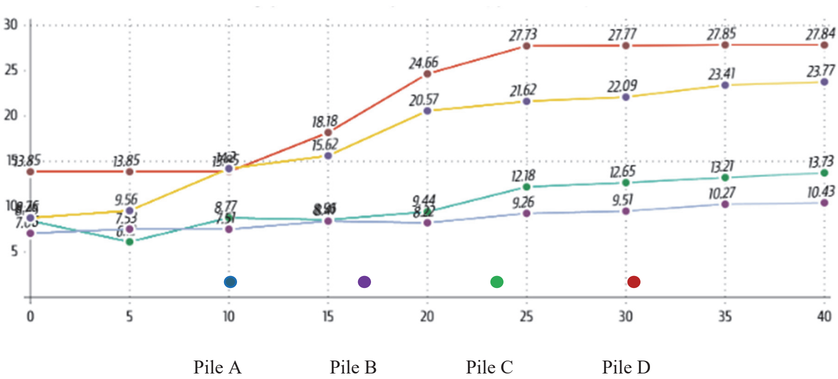

FIGURE 2. The rate of decomposition of food waste in the nutrition of worms [g·day^{-2}]
Source: own work.

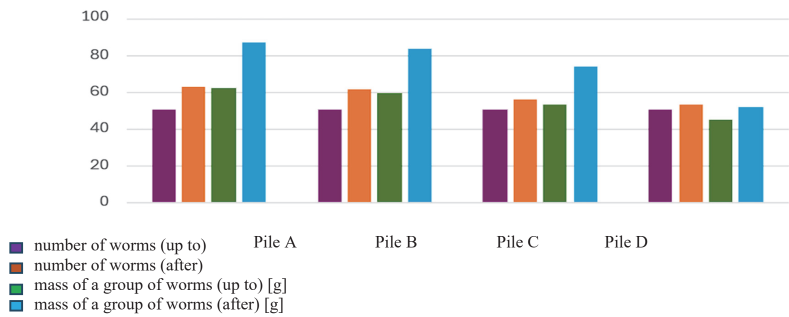

FIGURE 3. Changes in the mass and number of worms during the study
Source: own work.

The profile of the value of the hydrogen index, or pH of compost is important, since its introduction into the soil can change its degree of acidity, which, in turn, affects the availability of nutrients for plants. The pH profiles of the materials in the compostable samples used in the three tests are shown in Figure 4. In the first two weeks of the composting process, four samples (Pile A, Pile B, Pile C, Pile D) showed an increase in pH values. By the end of the second week, the pH values in samples A, B, C, and D were 5.9, 5.7, 5.6, and 5.7, respectively. This slight decrease in pH is associated with the release of acidic substances and their accumulation in the compostable material (Breitenbeck & Schellinger, 2004). At the beginning of the sixth week, the pH in all samples increased significantly, reaching 7.2, 6.5, 6.2, and 6.8 in samples of Piles A, Piles B, Piles C, and Piles D, respectively. This stage of pH increase is a thermophilic stage of the composting process, which is characterized by an increase in the rate of decomposition of the substrate, ammonification, and mineralization of organic nitrogen by microorganisms. By the end of the ninth week, a decrease in pH was again observed in the samples. The final product of all four samples (Pile A, Pile B, Pile C, Pile D) had pH values in the range of 6.3–7.5, which corresponds to a reasonable range for finished compost and is in the optimal range for use as a plant substrate (Hemidat et al., 2019).

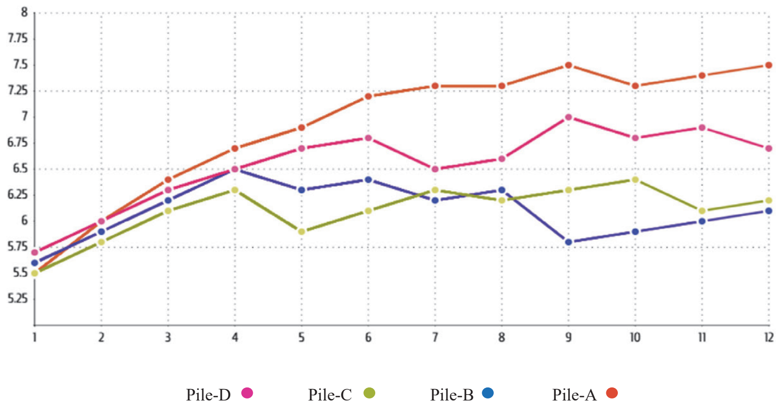

FIGURE 4. Average pH profiles during the composting period
Source: own work.

Thus, it could serve as an analogue of various technical means for solving problems associated with soil zooremediation, such as Californian red worms and wild earthworms. In particular, it was found that during the day, each worm passes through itself the amount of soil corresponding to the mass of the worm. In our earlier periods (planting density – 30 pieces·kg^{-2}, mass of worms – 0.6–1.0 g), this means that the studied worm species spend 1 kg of soil from their intestines in 1.5–2.0 months. Taking into account the moving volume of the total soil (an increase in the moving volume from comparing the average diameter of the worm's body and its intestinal diameter – from 1 : 3 to 1 : 5), the full mixing of this soil volume (1 kg) with worms can occur in 1.5–2.5 weeks.

It was necessary to prove the ability of worms to mix the soil in conditions of oil pollution compared to purely technical means. For this purpose, crude oil from fields in the Atyrau Region was introduced at the rate of 2.5 $g \cdot kg^{-2}$ (upper limit of low pollution). Earthworms were introduced in the amount of 15 $pieces \cdot kg^{-2}$. Determination of the amount of oil in substrates was measured weekly. Measurements of the average mass of worms and a visual assessment of their condition were carried out at the end of the experiment (Makhambetov et al., 2024).

The duration of the worm experiment was 180 days (from May to October), and they were not used for 91 days. In the first week of the experiment, in all cases, there is a significant decrease in the concentration of oil in the soil – from 3.8% with rare mixing to 14.3% with frequent mixing, and when using worms – 11.6%. In our opinion, this is largely due to the fact that light fractions fly out at the initial stage of oil pollution. At the next stages of the experiment, the effect of a constant increase in the zooremediation properties of Californian red worms and wild earthworms was revealed after evaporation of volatile oil fractions, adaptation of worms, natural selection of the most resistant individuals, as well as the birth of new individuals. In addition, it has been proven that mechanical mixing of the soil, even everyday, is not enough for effective biodegradation. *Eisenia fetida* increases its biomass by 40–50% in 90 days. The reproduction of earthworms was slow but maintained vitality. The key elements of the experiment are summarized in Table 3.

TABLE 3. Experimental data on the process of soil zooremediation

Parameter	Description/Observation
Earthworm species used	California red worms and common earthworms
Interaction with soil	Each worm processes a soil mass approximately equal to its body weight per day
Experimental setup	Worm density: 30 individuals per 1 kg of soil. Average worm mass: 0.6–1.0 g
Estimated soil processing time	The selected worm species can pass 1 kg of soil through their digestive systems within 1.5–2.0 months
Time for complete soil mixing	Based on average body and gut diameter ratios (1 : 3 to 1 : 5), complete mixing of 1 kg of soil may occur within 1.5 to 2.5 weeks
Research objective	To compare the efficiency of soil mixing by earthworms under oil contamination conditions with that of mechanical technologies
Study location	Oil-contaminated areas of the Atyrau Region (Kazakhstan)
Level of oil contamination	Crude oil added at a concentration of 2.5 $g \cdot kg^{-2}$ – representing the upper threshold of low contamination levels
Worm introduction rate	15 individuals per 1 kg of soil
Monitoring and measurements	Weekly measurement of residual oil content Final evaluation included average worm mass and visual health assessment

Source: own work.

Impact on the earthworms' biomass during the first 30 days; however, after a period of adaptation, growth was observed. *Eisenia fetida* demonstrated a high level of resilience, indicating its potential for effective use in vermiculture-based remediation technologies. Over the 90-day observation period, a significant reduction in petroleum residues (TPH) was recorded across all samples. The degradation rate was particularly higher in the samples where *Eisenia fetida* was introduced (Table 4).

TABLE 4. Level of decomposition of oil hydrocarbons

Pollution level [%]	Type of worm	Total petroleum hydrocarbons primary [mg·kg^{-2}]	After 90 days [mg·kg^{-2}]	Decomposition percentage [%]
0.5	*E. fetida*	5,000	1,200	76
0.5	rainworm	5,000	1,700	66
1.0	*E. fetida*	10,000	2,400	76
1.0	*Rainworm*	10,000	3,200	68
2.0	*E. fetida*	20,000	6,000	70
2.0	rainworm	20,000	7,800	61

Source: own work.

In the worm-free control samples, the oil decomposition rate was only about 25–30%. This is due to poor aerobic condition and low microbiological activity. The decomposition of hydrocarbons in the samples introduced by the *Eisenia fetida* worm was significantly higher when used. The high metabolic activity and the ability of this species to rapidly decompose organic substances have enhanced the transformation of oil components. Comparative analysis of indicators before and after animal remediation (Table 5).

TABLE 5. Changes in biological and agrochemical parameters of the soil

The indicator	Before and after	After (*E. fetida*)	After (*L. terrestris*)
Number of worms [pcs]	50	62–65	52–55
Biomass of worms [g]	60–65	85–90	50–55
Humus content [%]	1.2–1.5	2.0–2.4	1.7–1.9
Soil pH [-]	5.6–5.8	6.8–7.2	6.5–6.9
Level of biological activity	low	high	medium

Source: own work.

The humus content is one of the main indicators of the quality and ecological condition of the soil. Prior to the start of the experiment, oil–contaminated soils were characterized by a low level of humus (1.2–1.5%), a destroyed aggregate structure and low biological activity. Petroleum hydrocarbons inhibited the processes of mineralization and humus formation, which negatively affected soil fertility. During the experiment, it was found that the use of zooremediation with the participation of earthworms contributes to the restoration of the humus profile of the soil. In the samples with *Eisenia fetida*, the humus content increased to 2.0–2.4%, which corresponds to an increase of 35–60% compared to the initial values. This effect is due to the ingestion of coprolites enriched in organic substances, humic compounds, enzymes and trace elements into the soil. In the variants with *Lumbricus terrestris*, the increase in humus content was less pronounced and amounted to 1.7–1.9%, however, even these values indicate a positive trend in the restoration of soil fertility. At the same time, there was an improvement in the physico-chemical properties of the soil: the formation of a more stable granular structure, an increase in moisture capacity and stabilization of the reaction of the medium in the pH range 6.5–7.2.

Thus, zooremediation not only accelerates the degradation of petroleum hydrocarbons but also contributes to the formation of a secondary humus horizon, which is a key stage in restoring the ecosystem functions of the soil.

Conclusions

This study provides experimental evidence for the efficacy of vermiculture-based bioremediation as a viable strategy for the restoration of petroleum-contaminated soils under controlled laboratory conditions. The 90-day experiment demonstrated that the application of *Eisenia fetida* and native earthworms (*Lumbricus terrestris*) produced measurable and statistically significant improvements across all monitored parameters.

The principal findings of the study may be summarized as follows: total petroleum hydrocarbons (TPH) concentrations declined by 60–80% across all treatment groups, with the most pronounced degradation rates recorded in substrates inoculated with *Eisenia fetida*. This outcome is attributable to the synergistic interaction between earthworm gut-associated microbiota and indigenous hydrocarbon-oxidizing bacterial communities, which collectively accelerated the biochemical mineralization of hydrocarbon chains beyond the capacity of either biological agent applied in isolation.

Soil physicochemical parameters – including pH, organic matter content, moisture retention, and microbiological activity – improved significantly over the experimental period, indicating a progressive restoration of soil functional properties. Phytotoxicity indicators likewise declined, suggesting the re-establishment of conditions conducive to plant growth and ecosystem recovery. The concentrations of key macronutrients (nitrogen, phosphorus, potassium) increased in vermicompost-treated substrates, reflecting enhanced nutrient cycling mediated by earthworm activity.

Biometric monitoring revealed that, although worm biomass declined during the initial 30-day adaptation phase due to the acute toxic effects of residual petroleum compounds, both species subsequently entered a sustained growth phase, demonstrating the capacity for physiological adaptation to hydrocarbon-contaminated substrates. *Eisenia fetida* exhibited markedly superior stress tolerance, adaptive resilience, and remediation efficiency relative to native earthworms, which, while demonstrating measurable adaptation capacity, achieved consistently lower TPH reduction rates under equivalent experimental conditions.

Environmental and physicochemical parameters – including temperature, aeration, moisture content, and the carbon-to-nitrogen ratio – exerted a significant regulatory influence on worm survival, biomass accumulation, and hydrocarbon degradation rates. Optimization of these parameters represents a critical factor in maximizing the practical efficiency of vermiremediation technology under field conditions.

From an applied perspective, the results of this study confirm that vermiculture technology employing *Eisenia fetida* constitutes an environmentally sound, cost-effective, and scalable approach to petroleum soil remediation, with strong potential for industrial-scale implementation in the oil-producing regions of western Kazakhstan, where contaminated land areas exceed 194,000 ha. Given that the cumulative volume of oil sludge stockpiled across Kazakhstan is estimated at approximately 40 million tons, the widespread adoption of this biotechnology could contribute substantially to national soil remediation objectives.

Future research should address the long-term persistence of remediation effects beyond the 90-day observation window, the comparative performance of vermiculture across diverse soil types and contamination profiles, the optimization of worm-to-substrate ratios and organic amendment compositions, and the scalability of the method under varying climatic conditions characteristic of the Kazakh steppe and semi-arid zones. Additionally, the integration of vermiculture with complementary bioremediation approaches – such as phytoremediation and bioaugmentation – warrants systematic investigation as a means of further enhancing overall remediation efficiency.

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Summary

Experimental treatment of oil contaminated soil structure using vermiculture. Soil contamination with petroleum hydrocarbons represents one of the most critical environmental challenges in oil-producing regions of Kazakhstan, where approximately 59% of total oil-related soil pollution is concentrated in the Atyrau Region, with the total area of contaminated land exceeding 194,000 ha. This study investigated the potential of vermiculture-based bioremediation using Californian red worms (*Eisenia fetida*) and native wild earthworms (*Lumbricus terrestris*) for the restoration of petroleum-contaminated soils under controlled laboratory conditions. Experiments were conducted over a 90-day period using artificially contaminated soil samples with total petroleum hydrocarbons (TPH) concentrations of 0.5%, 1.0%, and 2.0%, supplemented with organic amendments. Physicochemical parameters – including pH, organic matter content, TPH levels, and microbiological activity – were monitored at regular intervals throughout the experimental period. Biometric assessments recorded changes in worm survival rate, biomass, and population dynamics. Key macronutrients (nitrogen, phosphorus, potassium), carbon-to-nitrogen (C : N), and temperature variations were determined using standardized laboratory methods. The central mechanism of remediation relied on the synergistic interaction between earthworm gut-associated microbiota and indigenous hydrocarbon-oxidizing soil bacteria, which collectively facilitated biochemical cleavage of hydrocarbon chains. The results demonstrated that vermiculture application facilitated TPH degradation of 60–80%, with the highest remediation efficiency observed in treatments involving *Eisenia fetida*,

which maintained an optimal C : N ratio and the greatest microbiological activity throughout the experiment. Zooremediation significantly enhanced soil microbiological activity, improved physicochemical soil properties, and increased the concentration of plant-available nutrients in the treated substrate. The findings suggest that vermiculture constitutes an environmentally sound, cost-effective, and scalable bioremediation technology with strong potential for large-scale application in petroleum-impacted regions of Kazakhstan.

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