Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received: 02 August 2026
Revised: 28 September 2026
Accepted: 12 October 2026

Natural Resources for Human Health 2026, Vol. 6 (6): 426–435

KEYWORDS:
Circular economy; eco-enzyme; environmental health; landfill management; organic waste.

Circular Economy Model for Organic Waste Recovery through Eco-Enzyme Production in Pamekasan Regency

Rita Parmawati[1], Prisca Kiki Wulandari[2], Indah Dwi Qurbani[3], Aya Shofiyah[4], Supriyanto[5], Muhammad Roil Bilad[6]

[1]Graduate School, Universitas Brawijaya, Malang 65145, Indonesia
[2]Department of Politics, Government, and International Relations (PPHI), Universitas Brawijaya, Malang, Indonesia
[3]Faculty of Law, Universitas Brawijaya, Malang, East Java 65145, Indonesia
[4]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya, Malang, Indonesia
[5]Environmental Agency of Pamekasan Regency, Indonesia
[6]Faculty of Integrated Technologies, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong BE 1410, Brunei Darussalam

ABSTRACT: This study evaluates a circular economy model combining source segregation, eco-enzyme fermentation, and derivative product development at the landfill serving Pamekasan Regency, Indonesia. An uncontrolled before-and-after assessment covered three months. The reported waste stream was 8,547.09 tons per month, including 4,700.90 tons of organic material. Month 3 diversion components totaled approximately 282 tons, equivalent to 6 percent of the organic fraction. Accepted eco-enzyme production totaled 16,790 liters. At assumed prices of IDR 5,000 to 8,000 per liter, estimated monthly gross revenue ranged from IDR 26.01 to 47.51 million. The optimistic scenario covered reported monthly operating costs from Month 2 onward. Odor intensity and fly and mosquito counts declined by 25.0, 43.9, and 50.7 percent, respectively, while leachate pH increased from 4.2 to 4.8. These uncontrolled changes cannot establish intervention effects or reduced disease burden. The model offers a pathway for local resource recovery, subject to verified material balances, product performance and safety, market demand, and complete cost accounting.

1. INTRODUCTION

Municipal solid waste (MSW) management is under increasing pressure from urbanization, population growth, and changing consumption patterns. In Southeast Asia, the large organic fraction of municipal waste makes biodegradable materials an important target for diversion from landfill disposal (Arumdani et al., 2021).

Indonesia faces persistent challenges in municipal solid waste management, particularly where collection and treatment infrastructure cannot accommodate incoming waste. Landfill-related contamination and air pollution can affect surrounding communities, making improved waste handling and environmental monitoring priorities for local management (Fajaruddin Natsir et al., 2021; Sumaryati et al., 2026). Planning based on the mapping of local resource availability has been used to support sustainable production management in East Java, making the mapping and monitoring of local conditions relevant as a basis for environmental management (Parmawati et al., 2018). Environmental quality also influences the performance of resource-based sectors in Indonesia; for instance, higher CO_2 emissions have been associated with lower livestock production, whereas income, education, and energy consumption showed positive associations (Wahyono et al., 2022).

Pamekasan Regency, situated on Madura Island in East Java Province, provides a local context for examining organic waste recovery (Ma'mun et al., 2023). The reported waste stream is 8,547.09 tons per month, of which 55 percent, or approximately 4,700.90 tons per month, is reported as biodegradable organic. This organic fraction provides a substantial potential feedstock for recovery. Landfill leachate and associated exposures are recognized environmental concerns, although local health effects were not measured in this study (Parvin & Tareq, 2021; Zahra et al., 2025).

The circular economy paradigm represents a structural departure from the conventional linear economic model, characterized by a take-make-dispose logic, toward a regenerative system in which resources are retained in productive use through iterative cycles of reuse, remanufacturing, and recycling (Nikolaou & Tsagarakis, 2021; Sönnichsen et al., 2024). Applied to the organic waste stream, circular economy principles translate into valorization strategies that transform biodegradable materials from liabilities into assets, generating economic value while simultaneously reducing environmental burden (Pal et al., 2024; Udourioh et al., 2026). The principles of the circular economy also emphasize waste reduction, biomass recycling, and the productive use of organic resources as part of a zero-waste approach (Parmawati & Supriyanto, 2026). Successful implementation in developing-country contexts, however, requires particular attention to local market conditions, social acceptance, and institutional enablers, as circular economy models imported directly from high-income settings frequently underperform when transplanted without contextual adaptation (Ahmed et al., 2022; Sungkono et al., 2025). The zero-waste approach can also be integrated into circular economy practices through the development of integrated systems that promote resource recovery and the productive use of residual materials, supporting more sustainable resource management (Parmawati et al., 2022).

Parmawati et al. (2023) emphasize that environmentally friendly supply chain practices can contribute to environmental sustainability by reducing waste generation and increasing the use of recycled and reused materials. In line with this principle, the utilization of organic waste and byproducts as value-added materials can support resource recovery (Desreza et al., 2022; Parmawati et al., 2026). These approaches align with circular economy principles by retaining resources in productive use.

Among the bio-conversion pathways available for organic waste valorization, eco-enzyme fermentation offers an accessible approach to recovering a liquid product from fruit and vegetable waste, sugar, and water. Published reviews describe its production, characteristics, and potential applications in domestic, agricultural, and environmental settings (Benny et al., 2023; Gumilar, 2023). However, the production of a fermented liquid does not by itself establish the efficacy or safety of its derivative products. Integrating fermentation into landfill operations therefore requires assessment of material flows, product quality, costs, and environmental indicators within the same operational setting.

This study examines a circular economy model centered on eco-enzyme production at the Pamekasan Regency landfill site. The research pursues four specific objectives: first, to characterize organic waste diversion through eco-enzyme production and source segregation; second, to evaluate reported eco-enzyme production and quality indicators; third, to assess operating costs and revenue under alternative price scenarios; and fourth, to describe changes in environmental indicators during implementation. The contribution is a site-specific assessment of the operational links and constraints between waste diversion, product recovery, and potential revenue, rather than a controlled test of environmental or public health effects.

2. MATERIALS AND METHODS

2.1 Research Design and Study Site

This study employed a quantitative approach with an uncontrolled before-and-after design, utilizing a pre-test-post-test comparison framework with reported monthly measurements over a three-month intervention period. Primary data were collected through direct observation, physical measurement, and structured data recording protocols implemented by trained research personnel (Fix et al., 2022). The reported waste stream at the Pamekasan Regency landfill site is 8,547.09 tons per month, with an organic fraction of 55 percent, equivalent to 4,700.90 tons per month. The site operates under a controlled landfill designation but exhibits characteristics of a semi-controlled open dump in practice, including inadequate leachate collection infrastructure and the absence of a gas capture system.

2.2 Circular Economy Model Design

The circular economy model comprised five integrated operational components arranged in a sequential value chain: incoming waste characterization and segregation; organic feedstock preparation; eco-enzyme fermentation; derivative product processing and quality assurance; and market linkage and commercialization (Figure 1). Organic waste reduction was achieved through two

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complementary pathways: direct diversion to eco-enzyme production, targeted at 2 percent of the organic fraction, and source segregation for recycling and composting, targeted at 3 to 4 percent of the organic fraction. An operational workspace of approximately 200 square meters was established within the landfill facility, and training was provided to six landfill workers on waste characterization, fermentation management, quality monitoring, and basic record-keeping.



Figure 1. Eco-enzyme circular economy value chain at the Pamekasan landfill site

2.3 Waste Segregation and Eco-Enzyme Fermentation Protocol

Incoming waste loads were subjected to a standardized characterization protocol. Random grab samples of at least 100 kilograms per load were sorted into seven waste categories, with weight fractions recorded using calibrated platform scales with an accuracy of plus or minus 0.5 kilograms. Fruit and vegetable waste was selected as the primary eco-enzyme feedstock and chopped into 1 to 3 centimeter pieces before fermentation. Eco-enzyme was produced using a substrate ratio of 3:1:10 by weight of organic waste, brown sugar, and water. Panataria et al. (2022) provide related work on eco-enzyme nutrient content. Fermentation was conducted in 25 to 30 liter high-density polyethylene vessels fitted with one-way gas release valves. After a stated 90-day fermentation, liquid was filtered through 100-mesh stainless steel mesh and assessed for pH, color, clarity, and odor.

2.4 Derivative Product Development and Economic Analysis

Accepted eco-enzyme was allocated to two derivative product formulations: liquid organic fertilizer, prepared by diluting eco-enzyme 1:500 with supplementary mineral nutrients, and natural cleaning agents, formulated at a 30:70 ratio of eco-enzyme to coconut-derived surfactant. Both products were packaged in HDPE bottles of 500 milliliter and 1,000 milliliter capacity with batch traceability coding. Economic performance was assessed from reported production costs and scenario-based gross receipts and operating balances. Scenario receipts equal accepted eco-enzyme liters multiplied by assumed IDR-per-liter prices, not documented sales of finished products. The assumed prices were IDR 5,000 and IDR 8,000 per liter. Revenue per kilogram of reported organic feedstock was also calculated; this measure does not deduct intermediate input costs and therefore is not net value added.

2.5 Environmental Health Measurement

Environmental indicators were measured at monthly intervals using a portable odor meter at five fixed monitoring points; a calibrated portable pH meter for leachate pH measurement at the site boundary drainage channel; and sticky fly traps together with BG-Sentinel mosquito traps deployed for 72-hour intervals at three monitoring stations.

2.6 Data Analysis

Quantitative data were analyzed using descriptive statistics, including means, ranges, and percentage change calculations. The analyses were paired t-tests or Wilcoxon signed-rank tests for pre-post comparisons at alpha equals 0.05. Since three monthly site summaries do not constitute independent intervention replicates; the reported p-values are not treated as validated inferential results, and the site-level changes are interpreted descriptively.

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3. RESULTS AND DISCUSSION

3.1 Waste Generation and Organic Fraction Reduction

The reported total waste stream was 8,547.09 tons per month, of which the organic fraction amounted to 4,700.90 tons per month (Table 1). The circular economy model targeted this organic fraction through eco-enzyme production and source segregation. Table 1 records eco-enzyme diversion of 31.34, 62.68, and 94.02 tons per month, alongside segregation of 141.03, 164.53, and 188.04 tons per month. These component masses imply combined diversion of approximately 3.67, 4.83, and 6.00 percent of the organic fraction, respectively (Table 1). The Month 3 components are consistent with the 6.0 percent total; the plotted source values in Figures 2–3 require reconciliation against the component masses. Reported segregation efficiency increased from 68 percent in Month 1 to 81 percent in Month 2 and 89 percent in Month 3 (Figure 2; Figure 3).



Figure 2. Organic waste flow: generation, diversion, and residual to the landfill cell

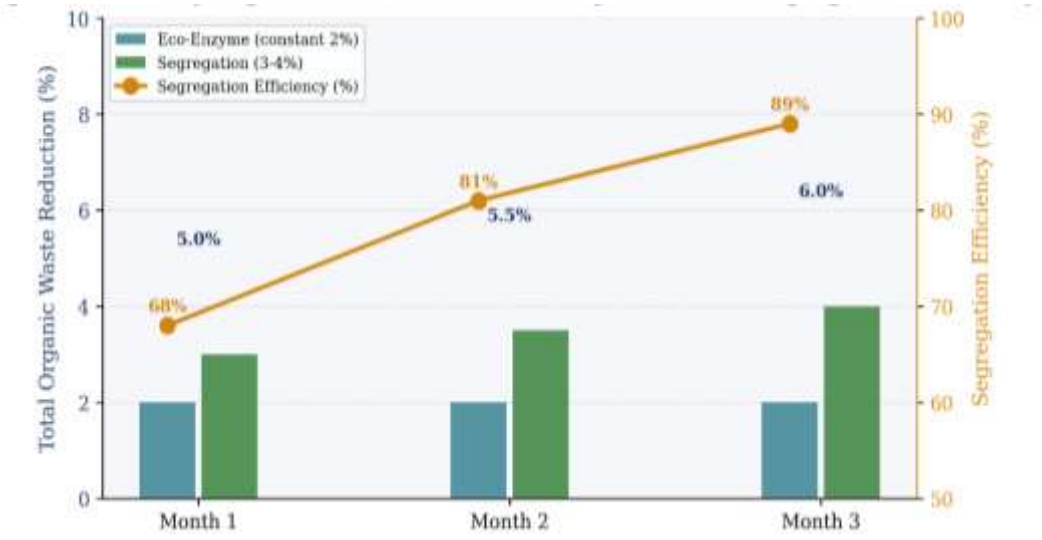


Figure 3. Monthly organic waste reduction composition and segregation efficiency

Table 1. Monthly Organic Waste Generation and Reduction

Parameter	Baseline	Month 1	Month 2	Month 3
Total MSW generated (tons/month)	8,547.09	8,547.09	8,547.09	8,547.09
Organic fraction, 55% (tons/month)	4,700.90	4,700.90	4,700.90	4,700.90
Diverted to eco-enzyme (tons/month)	0	31.34	62.68	94.02
Reduction via segregation (tons/month)	0	141.03	164.53	188.04
Total organic reduction (% of organic)	—	3.67%	4.83%	6.0%

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The Month 3 component masses indicate that most reported diversion came from source segregation rather than eco-enzyme production. This distinction matters because the combined reduction cannot be attributed to fermentation alone. Reported segregation efficiency increased from 68 to 89 percent, suggesting improved implementation, although the efficiency denominator requires clarification. Staff training and operational learning are plausible contributors to this pattern, but their individual effects were not isolated. Waste diversion performance also depends on local collection systems and market conditions, limiting direct comparisons across programs (Rahman et al., 2024).

3.2 Eco-Enzyme Production Yield and Quality

Table 2 reports organic feedstock processing of 94,018 kilograms in each month and accepted eco-enzyme volumes of 5,201, 5,650, and 5,939 liters, totaling 16,790 liters over the three-month study period (Table 2; Figure 4). The listed yields increase from 0.183 to 0.191 to 0.196 liters per kilogram, but they do not reconcile with accepted volume divided by the listed monthly feedstock, which gives approximately 0.055, 0.060, and 0.063 liters per kilogram. Batch rejection rates declined from 9.3 percent in Month 1 to 3.3 percent in Month 3.

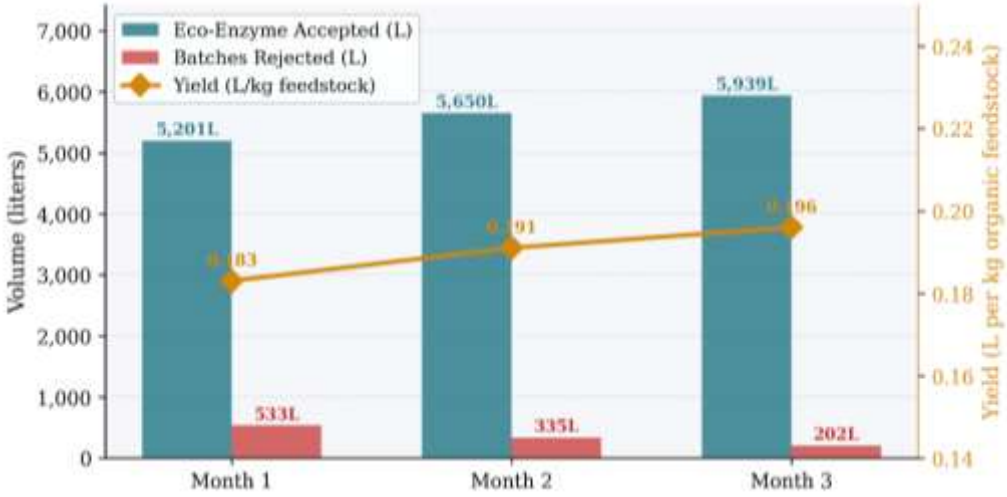


Figure 4. Eco-enzyme production volume, yield, and batch rejection rate by month

Table 2. Eco-Enzyme Production Summary by Month

Parameter	Month 1	Month 2	Month 3
Organic feedstock processed (kg)	94,018	94,018	94,018
Eco-enzyme accepted (liters)	5,201	5,650	5,939
Batch rejection rate (%)	9.3%	5.6%	3.3%
Reported yield (L/kg)	0.183	0.191	0.196

The simultaneous increase in accepted volume and decline in rejection rate is consistent with improved process control, but the data do not establish which operational changes produced the pattern. Feedstock composition, moisture content, fermentation duration, and filtration losses could influence recovered liquid volume. The discrepancy between listed feedstock, accepted volume, and yield prevents a defensible comparison with literature yields. Moreover, visual and sensory acceptance does not establish enzyme activity, nutrient suitability, antimicrobial efficacy, or product safety; those properties require corresponding analytical or application tests.

3.3 Derivative Product Development and Market Performance

Of the 16,790 liters of eco-enzyme accepted over three months, a reported 60:40 allocation was assigned to fertilizer and cleaner pathways, respectively (Figure 5). The IDR 5,000–8,000-per-liter range is treated as an assumed pricing scenario, not an observed market price. Product composition, efficacy, and safety have not been established.

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Figure 5. Product portfolio: (a)volume allocation and (b) revenue scenario analysis

Pilot fertilizer application with local agricultural cooperatives was reported. The finding implies that market development for natural cleaning agents required more sustained promotional effort. These experiences underline the need to distinguish product formulation, user acceptance, and verified performance when evaluating organic waste valorization pathways (Suhartini et al., 2022).

3.4 Economic Performance

Gross revenue under the conservative pricing scenario (IDR 5,000 per liter) increased from IDR 26.01 million in Month 1 to IDR 29.70 million in Month 3. Under the optimistic scenario (IDR 8,000 per liter), revenue increased from IDR 41.61 million to IDR 47.51 million over the same period. Total production costs declined from IDR 45.20 million to IDR 42.10 million (Table 3; Figure 6). Under the optimistic scenario, the monthly operating balance became positive from Month 2 onward, reaching IDR 5.41 million by Month 3. Under the conservative scenario, the model remained in operational deficit throughout the study period, ranging from negative IDR 19.19 million to negative IDR 12.40 million. These are conditional revenue estimates rather than evidence of realized sales or sustained profitability. Their validity also depends on whether the priced liters refer to accepted eco-enzyme or finished derivative products.

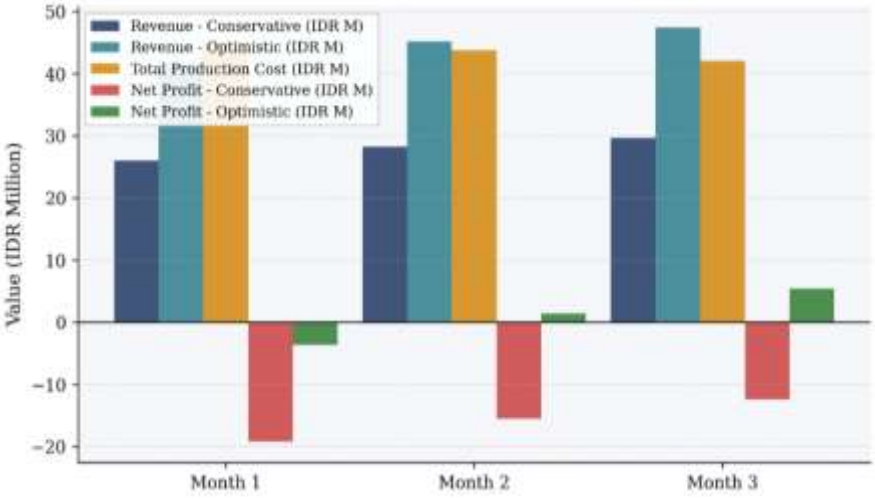


Figure 6. Monthly economic performance: revenue, production cost, and net profit

Table 3. Monthly Economic Performance Summary (IDR Million)

Economic Indicator	Month 1	Month 2	Month 3
Gross revenue, conservative (IDR M)	26.01	28.25	29.70
Gross revenue, optimistic (IDR M)	41.61	45.20	47.51
Total production cost (IDR M)	45.20	43.80	42.10
Modeled operating balance, conservative (IDR M)	−19.19	−15.55	−12.40
Modeled operating balance, optimistic (IDR M)	−3.59	+1.40	+5.41
Gross revenue per kg reported feedstock (IDR)	277	301	316

These results indicate that the model's operating balance is sensitive to selling price and cost coverage. Dividing reported production costs by accepted eco-enzyme volume gives an implied break-even price of approximately IDR 8,690 per liter in

Month 1 and IDR 7,089 per liter in Month 3, conditional on all accepted volume being saleable on that basis. Thus, the optimistic scenario covers the reported monthly costs only after the first month. The three-month optimistic balance totals approximately IDR 3.22 million, leaving little margin for omitted costs or unsold output. The gross-revenue-per-kilogram figures in Table 3 are approximately conservative scenario revenue divided by reported feedstock mass, not net value creation. Figure 6 retains the source label "net profit" for modeled operating balance; it does not demonstrate realized profit. Scaling could improve cost recovery only if demand, fermentation capacity, and unit costs support the expansion.

3.5 Environmental Health Outcomes

Pre-intervention baseline measurements recorded a mean odor intensity of 4 OU/m³ at monitoring points and a leachate pH of 4.2. Fly and mosquito counts stood at 248 and 67 per trap per 72 hours, respectively. Following three months of model implementation, odor intensity declined by 25.0 percent to 3 OU/m³, and leachate pH increased from 4.2 to 4.8 (Table 4; Figure 7). Fly counts declined by 43.9 percent to 139 per trap, and mosquito counts declined by 50.7 percent to 33 per trap. The reported Composite Pollution Index decreased from 3 to 2. These measurements describe environmental conditions and vector counts, rather than clinical health outcomes.

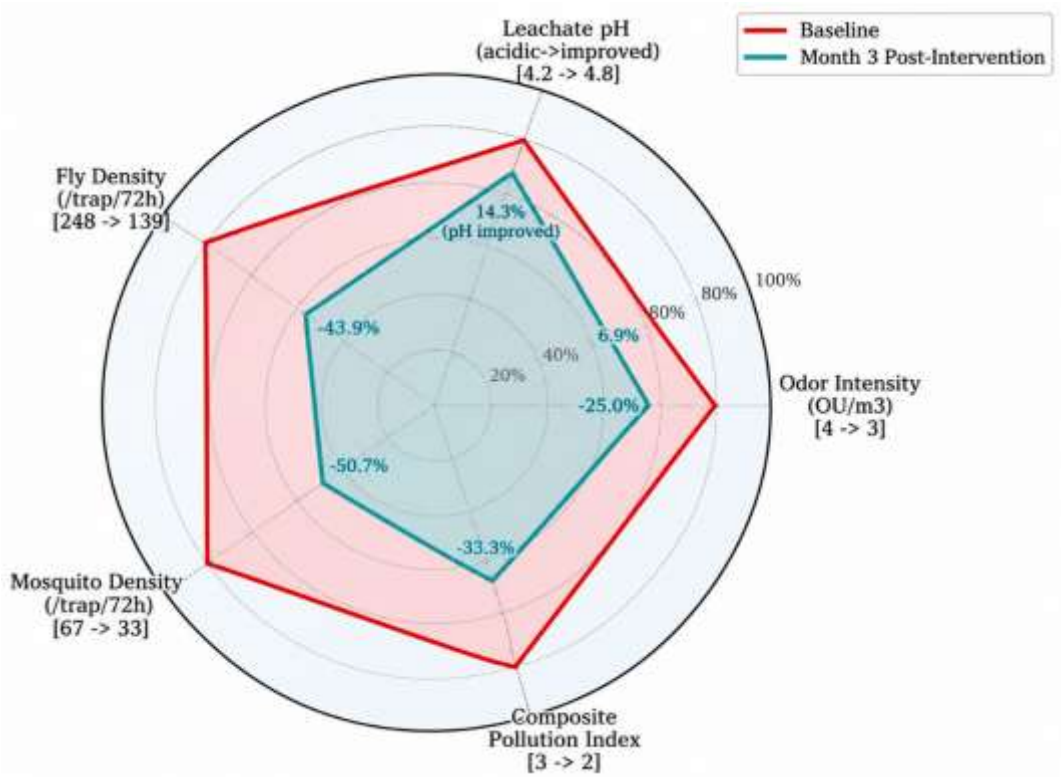


Figure 7. Environmental health indicators: baseline versus Month 3 post-intervention

Table 4. Environmental Health Indicator Changes Pre- and Post-Intervention

Indicator	Baseline	Month 3	Change
Mean odor intensity (OU/m³)	4	3	−25.0%
Leachate pH	4.2	4.8	+0.6 pH units
Fly count (per trap/72h)	248	139	−43.9%
Mosquito count (per trap/72h)	67	33	−50.7%
Composite Pollution Index	3	2	Not validated

The increase in leachate pH from 4.2 to 4.8 indicates reduced acidity, although the leachate remained acidic. Because pH is logarithmic, the +0.6-unit shift shown in Table 4 should not be interpreted as a proportional reduction in pollutant

concentration or toxicity. Reduced fresh organic loading is one possible explanation, but rainfall, dilution, waste age, and changes in leachate flow could also influence pH. Without organic acid concentrations, chemical oxygen demand, or comparable process measurements, the pH shift cannot establish a change in decomposition pathways or overall leachate treatment performance.

The reductions in fly and mosquito counts suggest lower trap catches during the observation period, but they do not establish reduced disease transmission. Trap catches may vary with weather, habitat availability, trapping conditions, and other site management activities. Species identification and health surveillance would be needed before linking the mosquito observations to dengue risk. Nonetheless, the Composite Pollution Index likewise cannot be interpreted as a validated pollution category until its calculation and thresholds are established. Figure 7 retains original percentage annotations for pH and CPI; these should not be read as validated pollutant-removal or pollution-risk estimates. The observations support continued environmental monitoring, while the absence of a control site prevents attribution of the changes to the intervention alone.

3.6 Policy Implications, Limitations, and Future Research

The Pamekasan model identifies practical requirements for further organic waste recovery, including reliable source segregation, sufficient fermentation capacity, product quality assurance, and market access. At the institutional level, implementation requires coordination among local government budget allocators, landfill operational staff, agricultural extension services, and product market intermediaries (Guerrero et al., 2013). Studies of multi-stakeholder collaboration in East Java report that weak coordination, limited field resources, inadequate understanding of actor roles, and the lack of a clear legal framework hinder effective collaboration, and they recommend clearer role definitions, guidelines, and training (Muktiyanto et al., 2025). Financing and regulatory recognition of waste-derived products may help support expansion, but eligibility for any specific funding instrument requires separate verification. Collaborative governance research shows that village-level regulations, facilitative leadership, and open dialogue among internal and external stakeholders support collaboration, while sustainability still requires further optimization (Nuh et al., 2024). Experience from the Gianyar Waste Recovery Project highlights the importance of context-specific conditions for program sustainability (Zurbrügg et al., 2012). In Pamekasan, expansion should follow reconciliation of material flows and verification of product performance, demand, and complete costs.

Several limitations constrain interpretation. The three-month study duration does not capture seasonal variation in organic waste composition, weather, or vector abundance. The absence of a control site limits attribution of environmental changes to the intervention. The 90-day fermentation period also requires explicit batch tracking to distinguish material loaded during the study from liquid harvested from earlier batches. Product efficacy and safety were not established by the reported acceptance indicators, and the economic scenarios do not establish sustained sales or full investment recovery. Future research should prioritize reconciled batch-level records, longitudinal monitoring for at least twelve months, controlled product testing, complete cost accounting, and comparative multi-site evaluation. A life cycle assessment should include sugar, water, surfactant and nutrient inputs, fermentation losses, packaging, and transport before net environmental benefits are inferred.

4. CONCLUSION

The Pamekasan case study illustrates how eco-enzyme fermentation and source segregation can be combined within a local organic waste recovery model. Reported accepted eco-enzyme production totaled 16,790 liters over three months, and the economic scenarios show that monthly cost recovery depends strongly on selling price. The Month 3 waste diversion components are consistent with a reduction of approximately 6 percent of the organic fraction, although plotted totals, feedstock records, and reported production yields require reconciliation. Odor and vector counts decreased and leachate pH increased during implementation; these uncontrolled observations cannot establish intervention effects or reduced disease burden. The model provides a basis for further site-specific evaluation, contingent on verified material balances, product performance and safety, market demand, and complete cost accounting. Wider deployment requires evidence beyond the present three-month assessment.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Universitas Brawijaya, the Indonesia Endowment Fund for Education (LPDP), and the National Research and Innovation Agency (BRIN) Contract No. 47/IV/KS/03/2026 and Contract No. 00190/DST/UN10.A0501/B/PT/2026, for their valuable support and contributions to this research. The authors sincerely appreciate the institutional and research support provided throughout the implementation and completion of this study.

AUTHOR CONTRIBUTIONS

Rita Parmawati: Conceptualization, Investigation, Writing – Original Draft.

Prisca Kiki Wulandari: Methodology, Laboratory Analysis.

Indah Dwi Qurbani: Data Curation, Formal Analysis.

Aya Shofiyah: Supervision, Writing—Review & Editing.

Supriyanto : Review & Editing

Muhammad Roil Bilad : Review and Editing

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Not applicable.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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