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Integrating Environmental Character Education and Eco-Enzyme Innovation for Community-Based Waste Management

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ABSTRACT

Background: Household organic waste in Indonesia, which accounts for over 40% of total solid waste, creates major environmental, economic, and health challenges, especially in semi-urban areas with limited waste management systems and low community participation. This study explores the potential of eco-enzymes as a community-based innovation to reduce organic waste while promoting ecological literacy and environmental citizenship.
Methods: A qualitative case study was conducted in Lebak Regency (September 2024–January 2025) involving households, schools, women's groups, youth organizations, farmers, and the local environmental agency. Data were collected through observation, interviews, focus group discussions, and document analysis, and were analysed thematically following the Miles and Huberman framework.
Results: The findings show that eco-enzyme training led to high adoption among participants, resulting in a noticeable reduction of household organic waste and methane emissions, while also strengthening community networks. Schools demonstrated higher levels of participation compared to households, indicating a gap between institutional practices and daily behaviour.
Contribution: This study contributes an integrative and replicable model that combines technical innovation with community empowerment.
Conclusion: Eco-enzyme interventions enhanced ecological literacy, encouraged pro-environmental behaviour, and supported local socio-economic activities, aligning with SDG 11.6 and 12.3. These findings highlight the importance of cross-sector collaboration linking schools, households, and communities for sustainable waste management.

1. Introduction

Waste management continues to pose a critical global challenge, affecting public health, ecosystem integrity, economic stability, and climate regulation [1]. Approximately 2.24 billion tons of municipal solid waste are generated annually worldwide, with nearly 50% originating from Asia; without targeted interventions, this volume is projected to increase by 70% by 2050 [2]. Rapid urbanization, population growth, and increasing per capita consumption are major drivers of this trend. Improper waste handling contributes not only to soil, water, and air pollution but also to greenhouse gas emissions, particularly methane from landfills, which is approximately 28 times more potent than CO_2, thereby exacerbating climate change and imposing substantial economic and public health burdens globally [3]–[6]. Despite these well-documented impacts, global waste management strategies remain fragmented and insufficiently integrated, underscoring the urgent need for innovative, scalable, and community-engaged solutions.

In Indonesia, municipal solid waste generation is projected to reach 22.5 million tons in 2024, predominantly organic, with food waste alone accounting for 40.9%, equivalent to approximately 184 kg per capita per year [1], [7]. This positions Indonesia among the world's top waste-producing nations, highlighting a critical environmental and public health challenge. Historical trends indicate a steady annual increase of 3–4% in urban waste generation over the past decade, suggesting that without strategic interventions, volumes may double by 2050. Current waste management infrastructure, including landfills and processing facilities, operates at limited capacity, with many sites exceeding safe operational thresholds. Consequently, the gap between waste generation and management capacity not only strains infrastructure but also undermines progress toward Sustainable Development Goals, particularly SDG 11.6, which targets effective urban waste management, and SDG 12.3, emphasizing the reduction of food waste and promotion of sustainable consumption [2], [8]. At the household level, limited ecological literacy, inadequate environmental education, and low participation in waste segregation exacerbate waste accumulation, reflecting that the challenge is not only technical but also socio-cultural in nature. This nationwide challenge is also evident at the regency level, where local governments face acute waste management pressures that mirror and, in some cases, intensify the broader national problem.

At the regency level, Lebak faces critical waste management pressures, with daily waste accumulation reaching approximately 10 tons. Key final disposal sites, including Dengung and Cihara, reportedly operate beyond their designed capacities, heightening the risk of environmental degradation and public health hazards [7]. Field observations indicate multiple environmental and health concerns, including methane emissions, groundwater contamination, localized flooding, and increased incidence of environment-related diseases such as diarrhea, respiratory infections, and dengue fever [9]–[11]. These impacts are further reinforced by technical limitations, including inadequate collection fleets, outdated processing technologies, and insufficient recycling facilities, which entrench reliance on landfilling and undermine circular economy principles as well as sustainable waste management objectives

[12]–[14]. This combination of systemic and technical constraints highlights the urgent need for integrated interventions that address capacity deficits while leveraging low-cost technological innovations.

Community-based interventions that combine citizen empowerment and environmental character education have consistently demonstrated greater effectiveness in promoting pro-environmental behaviors than technical solutions alone [15], [16]. One of the most promising community-based solutions is eco-enzyme, a fermented product derived from household food waste. Eco-enzyme works through a simple fermentation process, combining fruit or vegetable residues with sugar and water to produce enzymes and bioactive compounds capable of reducing organic waste and methane emissions, while minimizing reliance on synthetic chemicals and mitigating water pollution [9], [17]. Among these innovative approaches, eco-enzyme, a fermented product derived from household food waste, has emerged as a promising, cost-effective, and environmentally sustainable solution. Eco-enzyme can function as a biofertilizer, natural cleaner, organic pesticide, and disinfectant, directly supporting circular economy principles [18]–[21].

The fermentation process is straightforward, typically combining fruit or vegetable residues with sugar and water, producing enzymes and bioactive compounds capable of reducing organic waste and methane emissions, while minimizing reliance on synthetic chemicals and mitigating water pollution [9], [20]. Preliminary field studies in semi-urban contexts report reductions in household organic waste of approximately 35% over three months, indicating both environmental and socio-economic potential [22], [23]. School- and community-based applications enhance ecological literacy and environmental citizenship [8], [17]. However, effectiveness is influenced by factors such as raw material composition, fermentation conditions, and household engagement, highlighting the importance of integrating eco-enzyme application with environmental education and community participation strategies. Such integration not only enhances ecological literacy but also reinforces sustainable waste management behaviors, suggesting that eco-enzyme deployment is most successful when implemented alongside structured community empowerment initiatives.

Despite its demonstrated benefits, eco-enzyme adoption remains critically low and uneven across communities. Multiple interrelated barriers constrain uptake, variability in raw materials and fermentation uncertainties reduce reliability; low ecological literacy, coupled with perceptions that waste management is primarily a governmental responsibility, diminishes household engagement; and insufficient policy support limits scalability and sustainability [1], [24]–[26]. Consequently, household participation in community-based waste management initiatives often remains far below effective thresholds (~<15%), undermining potential reductions in organic waste and associated methane emissions. Comparative studies in Vietnam and China further emphasize that active social participation, combined with capacity-building interventions, is a decisive factor for successful waste reduction programs [27], [28]. Yet, despite these insights, no existing study has systematically examined a model

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that integrates eco-enzyme innovation with educational and community-based dimensions, leaving a significant research gap that this study seeks to address. These findings underscore the urgent need for integrative approaches that simultaneously address technical, educational, and institutional barriers, particularly in semi-urban contexts such as Lebak Regency, where socio-cultural norms, limited infrastructure, and variable community engagement present unique implementation challenges. However, no existing study has systematically examined a model that integrates eco-enzyme innovation with educational and community-based dimensions, leaving a significant research gap.

Despite growing interest in community-based waste management, no study has systematically examined a model that simultaneously integrates (i) technical innovation via eco-enzyme, (ii) environmental character education to enhance ecological literacy, and (iii) multi-level community empowerment strategies encompassing households, schools, women's groups, youth associations, and farmers, particularly in semi-urban contexts such as Lebak Regency. Existing interventions tend to focus on single components, limiting both behavioral adoption and measurable environmental outcomes. Building upon this identified gap, the present study develops and evaluates a comprehensive community-based eco-enzyme model with dual contributions.

Addressing this gap, the present study develops and evaluates a comprehensive community-based eco-enzyme model with dual contributions. Theoretically, it advances the integration of environmental character education frameworks, community empowerment theory, and circular economy principles, providing a structured approach to translate individual ecological awareness into collective action. Empirically, it generates robust field evidence on the model's effectiveness in: (1) reducing household organic waste through eco-enzyme application; (2) improving ecological literacy and fostering environmental citizenship; and (3) enhancing sustained active participation among diverse community actors.

This study further offers practical, actionable insights for local governments, schools, and community organizations, highlighting strategies to achieve SDG targets 11.6 and 12.3 while demonstrating scalable solutions for semi-urban waste management challenges [29]. By explicitly combining technical, educational, and social interventions, this research provides a novel, evidence-based approach with both theoretical rigor and measurable local impact. The objectives of this study are to: 1) Develop a community-based eco-enzyme model that integrates technical innovation, environmental character education, and community empowerment strategies; 2) Assess the model's effectiveness in reducing household organic waste and associated methane emissions; and 3) Evaluate changes in ecological literacy, environmental citizenship, and community participation resulting from the intervention.

Thus, this study fills a critical gap by systematically integrating eco-enzyme innovation, environmental character education, and community empowerment into a single comprehensive model. Unlike previous studies that addressed these aspects in isolation, the present research emphasizes their interconnection, offering both theoretical advancement and practical applicability. Theoretically, the study contributes to the development of an integrated framework that extends current environmental education and sustainability discourses. Practically, it provides actionable insights for semi-urban communities facing mounting waste management challenges, highlighting scalable strategies that align with the circular economy and community-based sustainability principles. This dual contribution underscores the novelty of the research and strengthens its relevance for academic, policy, and community stakeholders.

2. Method

2.1. Research Design

This study employed a qualitative exploratory case study to investigate household organic waste management using eco-enzyme in Lebak Regency, Banten, Indonesia. The study examined multi-stakeholder practices, perceptions, and social interactions to assess the role of eco-enzyme in community empowerment and environmental character education. Data were collected through participant observation, semi-structured interviews, focus group discussions (FGDs), and document analysis. Thematic analysis, guided by Miles, Huberman, and Saldaña [30] [31] [32], was applied to identify patterns and develop a community-based eco-enzyme model for semi-urban contexts.

2.2. Location and Duration

Research was conducted in Lebak Regency from September 2024 to January 2025, corresponding with a three-month eco-enzyme fermentation cycle. Sites were purposively selected based on high organic waste generation (40–45%), low waste segregation rates (>70% mixed), limited community engagement (<15% active participants in waste banks), and semi-urban infrastructural challenges [27] [28].

2.3. Participants and Sampling

Participants were purposively selected to represent multiple stakeholders involved in eco-enzyme household waste management [32]. The sample included 30 household heads (active, passive, non-users), 10 PKK facilitators, teachers, and youth representatives, 3 local DLH officials, and 7 environmental activists (N≈50), adjusted for data saturation. Triangulation across methods ensured diverse perspectives and validity.

2.4. Data Collection

Data were collected using complementary methods to enhance validity. Participant observation documented household waste-sorting practices, eco-enzyme production, and community interactions [33]. Semi-structured interviews explored perceptions, motivations, barriers, and impacts of eco-enzyme activities; all interviews were transcribed verbatim [34], [35]. FGDs (three sessions, 10 participants each) included stakeholders from urban, semi-urban, and rural areas to discuss challenges, empowerment, and educational outcomes. Document analysis covered local policies, waste-bank reports, training archives, and media coverage, contextualizing findings. To ensure validity, interview transcripts were returned to participants for member checking, FGD findings were cross-verified among participants, and observational records were triangulated with policy documents, training reports, and waste-bank archives. This iterative validation process enhanced the accuracy and credibility of the dataset prior to thematic analysis.

2.5. Procedure and Data Analysis

As seen in Figure 1, following Miles, Huberman, and Saldana [31], data analysis proceeded in four systematic steps: (1) data reduction: transcribed interviews, FGD notes, and observations were condensed and coded using NVivo software; (2) data display: coded data were organized into matrices and diagrams to identify relationships; (3) conclusion drawing and verification: emerging patterns were interpreted thematically; (4) validation: credibility was ensured through member checking, peer debriefing, and audit trails. In the coding process, descriptive and in vivo coding were first applied (first-cycle coding) to capture participants' own expressions, followed by pattern coding (second-cycle coding) to cluster categories into broader concepts. These categories were then refined through axial coding to construct overarching themes aligned with the eco-enzyme community model [31]. Three main themes were identified: (a) technical aspects (fermentation process, product quality, utility), (b) community empowerment (PKK, schools, youth, DLH), and (c) environmental character education (responsibility, care, sustainability).

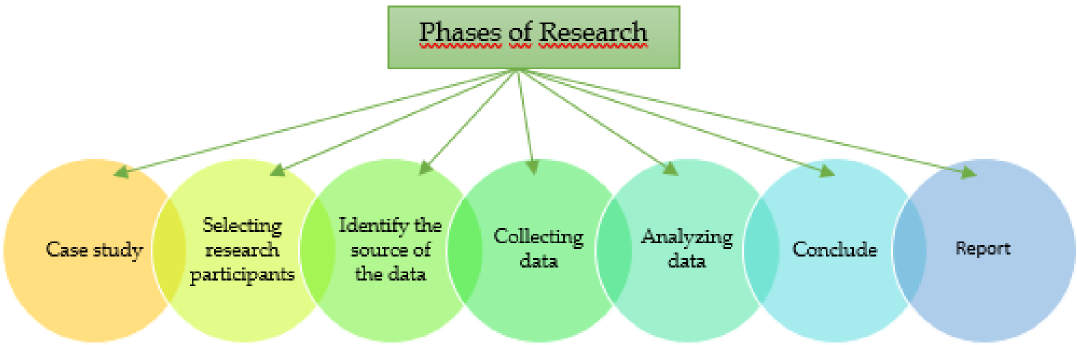

Figure 1. Research Stages

2.6. Trustworthiness

Trustworthiness followed Lincoln and Guba's criteria [36]. Credibility was ensured via prolonged engagement, triangulation of sources and methods, and member checking. Transferability was achieved through thick description of social and environmental contexts. Dependability relied on audit trails and peer debriefing, while confirmability was maintained through reflexive documentation. Ethical approval was obtained from the Research Ethics Committee of STAI Latansa Mashiro, Indonesia (Approval No: 124/KEPK/IX/2024), and written informed consent was secured from all participants before data collection. In addition to these measures, data validation was embedded throughout the collection process via member checking, participant cross-validation, and source triangulation, ensuring that interpretations remained faithful to participants' perspectives and contextual realities. These integrated procedures not only strengthened credibility, dependability, transferability, and confirmability but also enhanced the overall validity of the dataset and interpretations.

3. Results and Discussion

3.1. School as a Driver of Ecological Character Formation

Observations at MAN 1 Lebak show high institutionalization of environmental character education through routine clean-up activities, organic–inorganic waste separation, and student participation (~90%). As seen in Table 1, teacher interviews emphasize the importance of sustained habits. However, household surveys indicate only ~25% of families consistently separate waste, constrained by a lack of facilities (55% without separate bins) and perceived ineffectiveness (20% consider separation futile due to final mixing at TPS). This highlights a school–home gap, mirroring the value–action gap where pro-environmental knowledge is not automatically practiced at home [27], [28]. Facilities and structured programs improve school-level engagement, with average organic waste separation reaching 120 kg/week. The Theory of Planned Behavior suggests that high participation may enhance internalization of ecological values [14], [15].

Table 1. Pretest–Posttest School–Home Gap

Indicator	Pretest School (%)	Pretest Home (%)	Gap (%)	Posttest School (%)	Posttest Home (%)	Gap (%)
Waste Separation	90	25	65	92	60	32
Participation in Clean-up	85	30	55	87	55	32
Ecological Value Understanding	95	50	45	96	75	21

The largest gap was observed in waste separation practices. This suggests that while schools provide structured routines and peer-driven accountability, households often lack the infrastructure and social reinforcement necessary to sustain these behaviors. Limited access to proper waste bins, irregular collection systems, and insufficient local monitoring contribute to lower participation at the household level [1]. As seen in Figure 2, such structural limitations explain why technical practices that are easily institutionalized in schools become harder to replicate at home. Previous studies also emphasize that household environments are decisive in shaping sustainable waste behavior, where interventions and community empowerment significantly influence the adoption of waste segregation [9]–[11].

3.2. Community-Based Eco-Enzyme Training

As seen in Table 2, in Desa Sumur Bandung, 40 participants (10 students, 10 youth, 20 mothers) underwent eco-enzyme training covering concept, fermentation, recipes, and benefits. Post-training results indicate 80% successfully produced eco-enzyme meeting standards ($pH < 4$, fresh aroma, clear solution). FGD identified motivation (waste reduction, fertilizer production), barriers (difficulty in measuring ingredients), and replication strategies (small batches, weekly pH monitoring).

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Figure 2. School Environmental Activities

Table 2. Community-Based Eco-Enzyme Training Outcomes

Indicator	Pre	Post	Change (%)	Notes
Active Participants	0	30	-	≥80% session attendance
Fermentation Success (%)	0	90	+90	3 batches failed
Organic Waste Sorting Frequency	1	4	+300	At participant homes
Knowledge Score (0–10)	2	8	+300	Post-test
Pro-environmental Attitude (0–5)	2	4	+100	Self-report

Simulations suggest 20 households could process -100 kg of organic waste/week, reducing methane emissions by -50 kg/week [1], [3]. Key constraints include ingredient variation, fermentation precision, and monitoring. The eco-enzyme program reduced organic waste volume by approximately 80–90%. While this outcome demonstrates technical effectiveness, the wider implication lies in how experiential practices stimulate sustained behavioral change. Previous studies highlight that community-based waste management interventions can significantly strengthen participation and environmental responsibility when individuals directly observe the benefits of their actions [15], [16]. As seen in Figure 3 and Figure 4, this finding suggests that eco-enzyme practices not only reduced waste but also fostered a sense of environmental ownership, which is essential for sustaining long-term community participation in line with global recommendations for integrated waste management [1].

Figure 3. Development of Environmental Character at MAN Lebak

Figure 4. Documentation of the Eco-Enzyme Training

3.3. Eco-Enzyme Utilization for Natural Cleaning Products

Eco-enzyme is produced via anaerobic–semi-aerobic fermentation of organic waste, generating bioactive compounds with antibacterial and lipid-emulsifying properties. Standard quality: pH < 4, clear solution, fresh fermentation aroma. Produced eco-enzyme served as base for floor soap, dish soap, body soap, and laundry detergent. Formulations incorporate surfactants (MES) or natural alternatives (coco-glucoside, saponin), maintaining effectiveness while improving biodegradability.

Table 3. Eco-Enzyme-Based Household Cleaning Products

Product	Eco-Enzyme (ml/1000 ml)	MES (ml)	pH	Oil Removal (%)	Antibacterial (%)	Biodegradability (%)
Dish Soap	300	50	3.8	82	12 mm E. coli zone	70
Body Soap	300	40	3.9	75	10 mm	72
Laundry Detergent	300	45	3.7	80	11 mm	68
Floor Soap	300	30	3.7	78	9 mm	75

As seen in Table 3, variability in fermentation (25–40%), batches below standard) reflects differences in substrate ratios, process consistency, and SOP compliance, highlighting the need for structured community support. Documentation indicated strong student engagement in eco-enzyme projects. Beyond enthusiasm, this reflects the pedagogical role of experiential learning in shaping environmental literacy. Direct involvement enabled students to internalize abstract sustainability concepts through tangible practices, as also demonstrated in participatory eco-enzyme learning activities that enhance students' scientific understanding and responsibility [18]–[21]. As seen in Figure 5, this explains why eco-enzyme activities were not only well-received but also translated into deeper cognitive and affective learning outcomes, reinforcing previous findings that eco-enzyme projects significantly contribute to early environmental literacy and community-based sustainability education [37], [38].

Figure 5. Example of Eco-Enzyme Storage Container

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Figure 6. Stages of Eco-Enzyme Production

In Lebak, <30% of households have regular TPA access; >70% still burn mixed waste, emitting methane (~28× CO_2 global warming potential). As seen in Figure 6, eco-enzyme adoption can mitigate emissions: a household processing 3 kg/week could reduce ~12 kg/month of organic waste; scaling to 500 households could reduce 6 tons/month and ~0.84 tons CH_4/month. Products also provide economic incentives [37], [38]. BUMDes' involvement consolidates production, SOP/QC, marketing, and regulation compliance, closing the school–home gap and promoting circular economy benefits.

The findings demonstrate that schools serve as effective drivers of ecological character formation; however, the transfer of values from schools to households remains limited, reflecting a persistent value–action gap widely reported in semi-urban Asia [27], [28]. This study uniquely integrates school-based environmental education with community-driven eco-enzyme practices, bridging the school–home gap while promoting circular economy initiatives in a semi-urban area. Despite high student engagement in school-based waste separation (90%), household adoption remains low (25%), highlighting a persistent value action gap. The disparity suggests that institutional support alone does not guarantee behavior transfer, consistent with TPB, which emphasizes the role of perceived behavioral control and enabling conditions [15], [16]. This supports the Theory of Planned Behavior, which posits that knowledge and attitudes do not automatically translate into consistent behavior without enabling conditions and perceived behavioral control [14]. The novelty of this study lies in demonstrating how structured school programs and eco-enzyme training can significantly enhance environmental literacy and technical practices, while simultaneously exposing systemic barriers such as inadequate facilities, inconsistent infrastructure, and limited perceived benefits [39]. These findings confirm that knowledge internalization alone is insufficient without institutional and community support [15].

Community-based eco-enzyme training revealed strong potential for scaling waste reduction, as participants not only acquired technical competence but also began replicating practices at home. Community-based training not only enhanced technical competence (fermentation success 90%) but also fostered replicability at the household level, demonstrating participatory empowerment principles [37], [38]. Nevertheless, batch variability (25–40%) indicates the need for standardized SOPs and ongoing technical support [19], [40]. This aligns with participatory empowerment theory, which emphasizes that hands-on engagement enhances self-efficacy and motivation [37], [38]. Nonetheless, challenges in standardizing fermentation quality due to variations in resources highlight the need for precise standard operating procedures [19], [40]. While eco-enzymes offer advantages in terms of accessibility and affordability [29], [41], their limitations underscore the necessity of coupling community empowerment with technical support and monitoring systems [22].

The development of eco-enzyme–based cleaning products illustrates an innovative pathway toward circular economy practices, offering both ecological benefits and local economic opportunities [20], [42]. This aligns with the concept of waste valorization, whereby organic residues are transformed into marketable goods [17], [21]. The transformation of organic waste into cleaning products illustrates a circular economy approach, offering environmental mitigation and local income generation [20], [42]. Challenges in product consistency highlight the importance of institutional consolidation, e.g., BUMDes, to ensure quality, compliance, and scalability. However, dependence on surfactants, regulatory compliance, and quality consistency issues highlight the importance of institutional consolidation through village-owned enterprises (BUMDes) or similar entities [11] [43]. This consideration is particularly relevant for semi-urban areas with weak formal waste management services [9], [44], suggesting the potential generalizability of these findings to other Southeast Asian communities facing comparable infrastructure challenges.

This study is limited by its short duration, small sample size (40 participants), and semi-urban setting, which may restrict generalizability. Future research should consider longitudinal studies across multiple communities to assess sustained behavior and broader environmental impact. Overall, this study underscores that effective community empowerment requires the integration of school-based education, household engagement, and institutional support to overcome structural barriers. Eco-enzyme adoption demonstrates measurable environmental and socio-economic benefits, consistent with sustainable development principles [1], [45]. However, its long-term sustainability depends on technical standardization, governance, and continuous behavioral reinforcement. Multi-stakeholder collaboration linking schools, households, and local governance emerges as a replicable model for semi-urban communities seeking to bridge the school-home gap and foster a circular economy.

This research contributes novel insights by integrating school-based environmental education with community-driven eco-enzyme innovation, bridging the school–home gap and promoting circular economy practices. The approach demonstrates measurable environmental benefits (waste reduction, methane mitigation) and socio-economic potential (product commercialization) [1]. These findings directly support the achievement of Sustainable Development Goals (SDGs), particularly Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action), by highlighting methane emission mitigation through community-scale organic waste processing.

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Limited technology and low household participation reflect a "double burden" in semi-urban Asia [27] [28]. Eco-enzyme provides cost-effective, easy-to-apply solutions for organic waste management. School-based education significantly improves student understanding (25 → 75%), but household adoption remains ~35%, indicating a persistent implementation gap [30], [38]. Product derivatives (soap, detergent) present local economic potential, though regulation, quality, and surfactant choices must be managed [20].

4. Conclusion

This study provides evidence that household-scale eco-enzyme production offers an innovative and practical circular solution for organic waste management in semi-urban communities. The novelty of this study lies in integrating eco-enzyme production with environmental character education across school family community ecosystems, creating synergistic environmental, social, and pedagogical outcomes beyond conventional waste management interventions. Field trials demonstrated significant waste reduction, high fermentation success, and stable products.

For large-scale adoption, critical enabling conditions must be ensured, including standardized production protocols, community training, participatory monitoring systems, and local policy alignment. Future research should focus on longitudinal behavioral analyses, life-cycle and cost–benefit assessments, microbiological safety and agronomic efficacy testing, and experimental interventions to optimize family-centered environmental character education. This empirically validated, community-embedded model provides actionable pathways to replicate eco-enzyme-based waste management in semi-urban contexts, supporting SDG 11.6 and 12.3 while bridging technical innovation with sustainable social transformation.

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References

[1] U. and I. S. W. Association, *Global Waste Management Outlook 2024 - Beyond an age of waste: Turning rubbish into a resource*. United Nations Environment Programme, 2024.

[2] S. Kaza, L. Yao, P. Bhada-Tata, and F. Van Woerden, *What a waste 2.0: a global snapshot of solid waste management to 2050*. books.google.com, 2018.

[3] K. Calvin, "IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of

Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.," Jul. 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647

[4] V. Derosya and T. Ihsan, "The Role of Packaging in Food Loss and Waste Reduction: A Mini Review from Indonesia," *J. Serambi Eng.*, 2025, [Online]. Available: https://jse.serambimekkah.id/index.php/jse/article/view/1002.

[5] Y. Nurhayati and E. Triharyati, "The Interaction of Digital Lifestyle and Food Waste on Household Food Security among Urban Millennials: Evidence from Palembang City, Indonesia," *Equity J. Ekon.*, 2025, [Online]. Available: https://equity.ubb.ac.id/index.php/equity/article/view/582.

[6] R. Permatasari, I. Pratiwi, F. Hadinata, and M. I. Ammrullah, "Assessment of greenhouse gas (GHG) emissions in Indonesia using the first order decay (FOD) model: implications of waste bioavailability, biodegradability, and bioactivity," *Environ. Pollutants and Bioavailability*, 2025, https://doi.org/10.1080/26395940.2025.2539875

[7] K. L. Hidup, "Kehutanan.(2022). Sistem Informasi Pengelolaan Sampah Nasional (SIPSN)." 2024.

[8] A. S. Alqahtani, "Improve the QoS using multi-path routing protocol for Wireless Multimedia Sensor Network," *Environ. Technol. Innov.*, vol. 24, p. 101850, Nov. 2021, https://doi.org/10.1016/j.eti.2021.101850

[9] P. A. Jayasinghe, H. Jalilzadeh, and P. Hettiaratchi, "The Impact of COVID-19 on Waste Infrastructure: Lessons Learned and Opportunities for a Sustainable Future," *Int. J. Environ. Res. Public Health*, vol. 20, no. 5, p. 4310, Feb. 2023, https://doi.org/10.3390/ijerph20054310

[10] T. F. Ojo, O. A. Akpor, Y. J. Talabi, and A. S. Afolalu, "AI-Powered Platforms for Interactive Nutrition Education Based on WHO (World Health Organization) Guidelines–An Overview," *ABUAD J. of Engineering Research and Development*, 2025, https://doi.org/10.53982/ajerd.2025.0801.17-j

[11] H. H. Wicaksana, C. Parmanto, and M. Fauzi, "The Context of the Collaborative Governance Systems in Organic Waste Management is a Public Service in the Urban Area of Lebak Regency," *J. Manaj. Pelayanan Publik*, vol. 9, no. 2, pp. 327–352, Jun. 2025, https://doi.org/10.24198/jmpp.v9i2.61963

[12] G. Trancone, "Treatment of concrete waste from construction and demolition activities: Application of organic acids from continuous dark fermentation in moving bed biofilm reactors," *Chem. Eng. J.*, vol. 505, p. 159536, Feb. 2025, https://doi.org/10.1016/j.cej.2025.159536

[13] F. Lestari, "Spatiotemporal Trend of Hazardous Waste Sites and Risks in Urban Jakarta, Indonesia," *Sustainability*, vol. 17, no. 12, p. 5548, Jun. 2025, https://doi.org/10.3390/su17125548

[14] B. Moeini, "Effect of Household Interventions on Promoting Waste Segregation Behavior at Source: A Systematic Review," *Sustainability*, vol. 15, no. 24, p. 16546, Dec. 2023, https://doi.org/10.3390/su152416546

[15] S. Rahayu and S. Evanita, "Environmental Communication Strategy For Sustainable Waste Management Through Community Empowerment," *J. Bus. Stud. MANGEMENT Rev.*, vol. 7, no. 2, pp. 125–130, Jun. 2024, https://doi.org/10.22437/jbsmr.v7i2.33500

[16] Utami, Titis Istiqomah, and Lieza Corsita, "Implementation of Community-Based Waste Management to Improve Environmental Health in Villages," *Sustain. Appl. Modif. Evid. Community*, vol. 1, no. 2, pp. 1–8, Dec. 2024, https://gpijournal.com/index.php/samec/article/view/90

[17] S. C. Das, "Evaluating the biocatalytic potential of fruit peel-derived eco-enzymes for sustainable textile wastewater treatment," *Results Eng.*, vol. 21, p. 101898, Mar. 2024, https://doi.org/10.1016/j.rineng.2024.101898

[18] F. N. Arifah and E. C. Prima, "Testing the Antimicrobial Efficacy of Eco-Enzymes on Staphylococcus aureus and Escherichia coli as a Participatory Student Activity in Biotechnology Material for Food Waste Management," *Symbiotic J. Biol. Educ. Sci.*, vol. 6, no. 1, pp. 1–10, Apr. 2025, https://doi.org/10.32939/symbiotic.v6i1.156

[19] and F. S. R. Halim, M. Jaya Arma, "Chemical Characteristics of Eco-enzymes as Liquid Organic Fertilizer from Vegetable Waste and Its Impact to Improve the Growth of Red Onion (Allium ascalonicum L.) on Marginal Dry Land," *Int. J. Agric. Biosci.*, 2025, https://doi.org/10.47278/journal.ijab/2025.050

[20] R. Rachman, S. A. Yanti, and N. O. Abdullah, "Innovative Eco-Enzyme from Fruit and Vegetable Waste for Pollution Control," *Gema Lingkung. Kesehat.*, vol. 23, no. 1, pp. 14–19, Jan. 2025, https://doi.org/10.36568/gelinkes.v23i1.142

[21] C. Vidalia, E. Angelina, J. Hans, L. H. Field, N. C. Santo, and E. Rukmini, "Eco-enzyme as disinfectant: a systematic literature review," *Int. J. Public Heal. Sci.*, vol. 12, no. 3, p. 1171, Sep. 2023, http://doi.org/10.11591/ijphs.v12i3.22131

[22] H. Maulida, W. Herwina, and A. Hamdan, "Pelatihan Eco Enzyme Sebagai Alternatif Pengolahan Sampah," *JENTRE*, vol. 4, no. 2, pp. 85–93, Dec. 2023, https://doi.org/10.38075/jen.v4i2.465

[23] A. Sarminingsih, "Study of the Effect of Adding Eco-Enzyme to the Process of Decomposing Organic Waste on the Quality of Compost, Leachate, and Methane Gas Production," *J. Presipitasi Media Komun. dan Pengemb. Tek. Lingkung.*, vol. 20, no. 3, pp. 655–668, Dec. 2023, https://doi.org/10.14710/presipitasi.v20i3.655-668

[24] H. Kriswantoro, "Utilization of Eco-Enzyme from Household Organic Waste to Maintain Soil Fertility and Plant Pest Control," *Altifani J. Int. J. Community Engagem.*, vol. 3, no. 1, p. 7, Dec. 2022, https://doi.org/10.32502/altifani.v3i1.5355

[25] S. S. Sawant, H.-Y. Park, E.-Y. Sim, H.-S. Kim, and H.-S. Choi, "Microbial Fermentation in Food: Impact on Functional Properties and Nutritional Enhancement - A Review of Recent Developments," *Fermentation*, vol. 11, no. 1, p. 15, Jan. 2025, https://doi.org/10.3390/fermentation11010015

[26] I Nengah Muliarta, Desak Ketut Tristiana Sukmadewi, Gede Agus Surya Pratama, I Nyoman Yoga Parawangsa, and Ni Luh Putu Putri Setianingsih, "Youth Involvement in Processing Kitchen Waste into Eco-Enzyme as Air Freshener in Sanur Kauh Village - Denpasar City," *Asian J. Community Serv.*, vol. 2, no. 9, pp. 759–776, Sep. 2023, https://doi.org/10.55927/ajcs.v2i9.6145

[27] A. T. Nguyen, N. Nguyen, P. Phung, and N. Yến-Khanh, "Residents' waste management practices in a developing country: A social practice theory analysis," *Environ. Challenges*, vol. 13, p. 100770, Dec. 2023, https://doi.org/10.1016/j.envc.2023.100770

[28] W. Yao and X. Zhou, "Acceptance of pay-as-you-throw solid waste charging methods

among urban residents in China," *Front. Environ. Sci.*, vol. 11, Aug. 2023, https://doi.org/10.3389/fenvs.2023.1263565

[29] N. Benny, R. Shams, K. K. Dash, V. K. Pandey, and O. Bashir, "Recent trends in utilization of citrus fruits in production of eco-enzyme," *J. Agric. Food Res.*, vol. 13, p. 100657, Sep. 2023, https://doi.org/10.1016/j.jafr.2023.100657

[30] V. Braun and V. Clarke, "Reflecting on reflexive thematic analysis," *Qual. Res. Sport. Exerc. Heal.*, vol. 11, no. 4, pp. 589–597, Aug. 2019, https://doi.org/10.1080/2159676X.2019.1628806

[31] M. B. Miles, A. M. Huberman, and J. Saldana, "Qualitative data analysis, A methods sourcebook (fourth)," *Arizona State University*. 2019.

[32] G. Guest, E. Namey, and M. Chen, "A simple method to assess and report thematic saturation in qualitative research," *PLoS One*, vol. 15, no. 5, p. e0232076, May 2020, https://doi.org/10.1371/journal.pone.0232076.s001

[33] H. Kallio, A. Pietilä, M. Johnson, and M. Kangasniemi, "Systematic methodological review: developing a framework for a qualitative semi-structured interview guide," *J. Adv. Nurs.*, vol. 72, no. 12, pp. 2954–2965, Dec. 2016, https://doi.org/10.1111/jan.13031

[34] M. S. Alam, A. Asmawi, and S. Fatema, "Focus Group Discussions (FGDs) for Qualitative and Mixed-Method Approaches: Principles, Applications, and Key Considerations," *Integr. J. Res. Arts Humanit.*, vol. 5, no. 4, pp. 51–56, Jul. 2025, https://doi.org/10.55544/ijrah.5.4.8

[35] N. K. Bachtiar, M. Fariz, and M. S. Arif, "Conducting a Focus Group Discussion in Qualitative Research," *Innov. Technol. Entrep. J.*, vol. 1, no. 2, pp. 94–101, Aug. 2024, https://doi.org/10.31603/itej.11466

[36] I. Korstjens and A. Moser, "Series: Practical guidance to qualitative research. Part 4: Trustworthiness and publishing," *Eur. J. Gen. Pract.*, vol. 24, no. 1, pp. 120–124, Jan. 2018, https://doi.org/10.1080/13814788.2017.1375092

[37] D. Deviona, "Grounding Eco-Enzyme to The Community Of Air Putih Urban Village Through Education and Socialization Of Household Organic Waste Processing," *J. Community Engagem. Res. Sustain.*, vol. 3, no. 1, pp. 55–62, Jan. 2023, https://doi.org/10.31258/cers.3.1.55-62

[38] A. Hidayat, "Community Empowerment and Environmental Management through Eco Enzyme Production Training in Kismoyoso Village, Boyolali – Central Java," *Prospect J. Pemberdaya. Masy.*, vol. 2, no. 2, pp. 114–120, Jul. 2023, https://doi.org/10.55381/jpm.v2i2.147

[39] R. T. Wahyuni, D. A. Putri, M. L. Al-Ghozi, and Fatmawati, "Pengelolaan Sampah Di Lingkungan Pasar Arengka Dan Pengaruhnya Terhadap Lingkungan Sekitar," *J. Pendidik. Sos. dan Humaniora*, 2025, [Online]. Available: https://publisherqu.com/index.php/pediaqu/article/view/3074.

[40] N. O. Abdullah, A. Zubair, N. A. P. Mangarengi, R. M. Rachman, M. Tumpu, and D. Djamaluddin, "Identification of eco enzyme characteristics from organic waste," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1268, no. 1, p. 012015, Dec. 2023, https://doi.org/10.1088/1755-1315/1268/1/012015

[41] and M. F. F. G. G. Gumilar, A. Kadarohman, "Characterization and Enzymatic

Evaluation of Ecoenzyme Derived from Fruit and Vegetable Waste: An Effort to Achieve Zero Waste Concept," *Baghdad Sci. J.*, 2024, https://doi.org/10.21123/bsj.2024.10707

[42] B. Varshini and V. Gayathri, "Role of Eco-Enzymes in Sustainable Development," *Nat. Environ. Pollut. Technol.*, vol. 22, no. 3, pp. 1299–1310, Sep. 2023, https://doi.org/10.46488/NEPT.2023.v22i03.017

[43] I. A. M. Herawati, I. B. K. Sindu Putra, and I. W. Suyanta, "Meningkatkan Literasi Lingkungan Anak Usia 5-6 Tahun Melalui Projek Eco Enzyme," *Kumara Cendekia*, vol. 11, no. 3, p. 251, Oct. 2023, https://doi.org/10.20961/kc.v11i3.76862

[44] F. A. Kitole, T. O. Ojo, C. U. Emenike, N. Z. Khumalo, K. M. Elhindi, and H. S. Kassem, "The Impact of Poor Waste Management on Public Health Initiatives in Shanty Towns in Tanzania," *Sustainability*, vol. 16, no. 24, p. 10873, Dec. 2024, https://doi.org/10.3390/su162410873

[45] U. K. Priya and R. Senthil, "Framework for Enhancing Urban Living Through Sustainable Plant Selection in Residential Green Spaces," *Urban Sci.*, vol. 8, no. 4, p. 235, Dec. 2024, https://doi.org/10.3390/urbansci8040235