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A Community Empowerment Model for Source-based Organic Waste Reduction in a Secondary City, Banjarbaru, Indonesia

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Abstract

Secondary cities in developing countries face increasing pressure on municipal waste systems due to limited infrastructure capacity and high organic waste fractions. While decentralized organic waste management has been widely promoted, empirical medium-term evidence demonstrating measurable and sustained impacts at the household level remains limited. This study evaluates a six-month community empowerment intervention involving 30 households in a secondary Indonesian city. The intervention integrated environmental literacy, flexible low-cost treatment technologies, repeated facilitation, and neighborhood-level institutional reinforcement. A paired pre–post design was applied to assess changes in household organic waste entering the municipal collection system. Statistical analysis included paired t-test, Wilcoxon signed-rank test, effect size estimation, and 95% confidence interval calculation. The intervention produced a statistically significant reduction of 52.30% in household organic waste generation, equivalent to a mean decrease of 1.71 kg per household per day (95% CI: 1.50–1.91; $t(29) = 16.78$, $p < 0.001$). The effect size was exceptionally large (Cohen's $d = 3.06$), indicating substantial and sustained behavioral adaptation rather than short-term compliance. Behavioral interpretation was informed by the Theory of Planned Behavior (TPB) framework and supported by qualitative observations. Findings demonstrate that source-based organic waste reduction can function as a scalable socio-technical micro-governance strategy in infrastructure-constrained urban contexts. The integrated four-layer empowerment model provides a replicable framework for secondary cities seeking low-cost, behavior-centered waste management solutions. The study reframes decentralized organic waste treatment as a governance mechanism capable of producing quantifiable environmental outcomes rather than merely a technical intervention.

Keywords: community empowerment; source-based waste reduction; household organic waste; decentralized composting; secondary cities

1. Introduction

Urban waste management faces challenges due to urbanization and changing consumption patterns. Many cities around the world still rely on a "collect-transport-dispose" waste management system. Meanwhile, efforts to reduce waste at source are lacking. Developing countries in Asia and Africa show low levels of source segregation and reliance on landfills (Zhang et al., 2024). Consequently, municipal waste management costs continue to increase. Organic waste, such as food scraps, constitutes the most common type of municipal waste. The lack of source segregation results in mixed waste when disposed of at landfills. Meanwhile, organic waste at landfills

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significantly impacts emissions and waste system performance (Scharff et al., 2023). Therefore, source separation and decentralized organic waste processing are considered important upstream waste management strategies.

Organic waste segregation has been shown to reduce waste volume at landfills. Ecological and economic impact studies demonstrate significant potential for reducing landfill load while enhancing composting or other biological processes (Maletz et al., 2025). However, its success is highly dependent on community, government, and regulatory involvement. Various studies demonstrate the importance of designing social interventions to enhance community participation. Programs that integrate environmental education, facility provision, ongoing engagement, and strengthening social fabric are more effective than one-time campaigns (Trushna et al., 2024). A continuous and contextualized behavior-based approach is crucial for sustaining sorting practices (Moeini et al., 2023). Technically, household- and community-scale composting is a widely studied option. This system can significantly reduce the volume of organic waste if initial sorting and waste management are carried out consistently (Manea et al., 2024). Composting can reduce pressure on municipal waste infrastructure, provided that sorting compliance and sustained social support are maintained (Rao & Parsai, 2023).

In Indonesia, organic waste management, such as composting, has the potential to reduce waste, but is still hampered by low public awareness (Farahdiba et al., 2023). At this stage, the main challenge lies not in technology itself, but in behavioral adaptation and community social systems. Active community participation and social education are key factors in adaptive waste management. Bibliometric analysis indicates collaborative governance and a public participatory framework as prerequisites for long-term success (Zebua et al., 2025). A study in Thailand demonstrated the strategic potential of local leadership and public participatory mechanisms in maintaining the sustainability of community-based initiatives (Leknoi et al., 2024). Policy instruments that combine environmental education and strengthening local institutions have been shown to improve waste sorting performance (Galavote et al., 2024). Other studies have shown that subjective norms and perceived behavioral control influence household decisions to sort organic waste (Etim et al., 2024). These findings underscore the need for integrated technical interventions and behavior change strategies within the community.

The present study adopts the Theory of Planned Behavior (TPB) as a behavioral interpretation framework. According to the Theory of Planned Behavior (TPB), pro-environmental behavior is influenced by attitudes, subjective norms, and perceived behavioral control (Ajzen, 1991; Etim et al., 2024). Previous studies have demonstrated that household waste separation behavior is strongly influenced by these dimensions, particularly when reinforced through repeated social interaction and contextual facilitation. In this study, TPB serves as a behavioral interpretation framework for understanding household participation and waste reduction practices during the intervention period.

Technical and economic evaluations indicate that a community-based composting model in small and medium-sized cities is financially and operationally feasible with effective local community support (Oviedo et al., 2025). Source-based waste reduction contributes to lowering environmental impacts (Ramzy et al., 2025). System simplicity and consistent social reinforcement are key factors for long-term compliance (Naujokas & Bobinaite, 2025). While these findings reinforce the importance of source separation and decentralized organic processing, there remains a lack of medium-term empirical studies that quantitatively evaluate the impact of community empowerment in secondary cities such as Indonesia. Existing research tends to focus on macro policies and short-term experiments, while systematic documentation of measurable impacts on organic waste reduction is limited. Several recent studies have primarily emphasized technical efficiency, landfill diversion potential, or policy implementation (Maletz et al., 2025; Manea et al., 2024; Rao & Parsai, 2023), while less attention has been given to sustained behavioral adaptation and the role of local neighborhood institutions in maintaining household participation over time (Trushna et al., 2024; Moeini et al., 2023; Zebua et al., 2025). In addition, studies discussing decentralized organic waste management in developing urban areas remain relatively limited, particularly in non-metropolitan cities with constrained municipal waste management capacity (Zhang et al., 2024; Farahdiba et al., 2023). Most existing studies also rely on short-term pilot projects or cross-sectional approaches, making it difficult to understand the medium-term dynamics of community participation and behavioral adaptation in decentralized organic waste management systems (Trushna et al., 2024; Moeini et al., 2023; Naujokas & Bobinaite, 2025).

This study fills this gap through a community-based intervention in Cempaka Village, Banjarbaru City. The aim is to evaluate changes in household organic waste generation and analyze the dynamics of community behavioral adaptation and participation during the intervention. Using pre-post intervention methods and periodic monitoring, this study measures the extent of waste reduction and formulates a replicable operational model for community empowerment. Unlike previous studies that mainly focus on technical intervention outcomes, this research integrates behavioral approaches, simple decentralized waste processing technologies, periodic community facilitation, and neighborhood-based institutional participation within a single intervention framework. The study therefore contributes not only to quantitative evidence of household organic waste reduction, but also to the development of an operational community empowerment model applicable to secondary urban contexts in developing countries. Furthermore, this study provides medium-term empirical observations that help explain how continuous facilitation, social reinforcement, and contextualized environmental education influence the sustainability of household waste sorting practices (Trushna et al., 2024; Moeini et al., 2023; Zebua et al., 2025; Naujokas & Bobinaite, 2025). This research contributes to strengthening source-based waste governance with technical and social integration and provides an empirical basis for sustainable urban planning.

2. Methods

This study used a quasi-experimental pre-post design without a control group, with periodic organic waste measurements conducted monthly over six months. In community-based waste management program evaluations, a quasi-experimental approach is commonly used to assess measurable changes over time (Shadish et al., 2002). Impact evaluation was conducted through a pre- and post-intervention comparison (O'Cathain, 2020), and is commonly applied in household waste sorting studies to detect behavioral changes and organic waste reduction in natural social settings (Trushna et al., 2024; Moeini et al., 2023). The study adopted a longitudinal household-based intervention design to observe changes in waste generation and community participation patterns over a medium-term implementation period. The study was conducted over six months in neighborhood association (RT) 40, Cempaka Village, Banjarbaru City, Indonesia. The study location was chosen because it did not yet have an organic waste sorting system and had an active neighborhood association (RT) structure. The area also represents a typical secondary urban residential setting characterized by mixed household activities and limited decentralized waste management practices. A total of 30 households were recruited through purposive sampling based on a voluntary commitment to participate in the six-month intervention. Because participation was voluntary, the study may be subject to self-selection bias, as participating households may possess higher baseline environmental awareness and motivation than the general population. This limitation was considered during interpretation of the findings. Selection criteria included permanent residency within the RT area, willingness to participate throughout the intervention period, and agreement to conduct household-level organic waste segregation and periodic monitoring. Households served as the primary unit of analysis and represented the point of waste generation and behavioral decision-making, while the RT served as a coordinating structure and reinforced social norms at the local level.

Figure 1. Geographic context of the study site in Cempaka District, showing proximity to key urban nodes and regional transport corridors

The intervention was designed as an empowerment model based on four integrated components: environmental education, waste management training, waste management facilitation, and institutional strengthening. Structured educational sessions addressed the environmental impacts of organic waste and the importance of source segregation, with the aim of strengthening environmental attitudes, subjective norms, and pro-environmental behaviors (Etim et al., 2024). Technical training introduced low-cost processing methods such as biopores, stacked bucket composters, Takakura, and eco-enzymes, with options tailored to environmental and community conditions, in line with recommendations for contextual technology adoption (Manea et al., 2024; Farahdiba et al., 2023). Facilitation provided reinforcement, feedback, and problem-solving, as repeated engagement has been shown to increase long-term behavioral stability (Moeini et al., 2023). These practices were institutionalized through the neighborhood unit (RT) as a coordination center. Integration into local governance structures can enhance the sustainability of environmental behavior (Zebua et al., 2025). The intervention was implemented without financial incentives so that observed changes reflect internalized behavioral adaptation. Community assistance activities included periodic monitoring visits, informal discussions, technical troubleshooting, and reinforcement of household participation conducted throughout the intervention period.

Organic waste generation was monitored periodically and summarized monthly to reduce short-term reporting fluctuations. Households were instructed to separate organic waste from other domestic waste streams before weighing. Organic waste included food scraps, vegetable residues, fruit peels, and other biodegradable kitchen waste generated from daily household activities. Organic waste data were obtained through household-level self-weighing conducted by participating residents using available weighing scales within their domestic settings. The reported values were subsequently converted into kilograms per household per day for analysis. Because measurements relied partly on household self-reporting, some degree of reporting inaccuracy may have occurred despite periodic monitoring and follow-up discussions during the intervention period. Baseline measurements were conducted prior to the intervention to obtain the average household organic waste generation per day, followed by periodic measurements throughout the implementation phase. Post-intervention values reported in the statistical analysis represent the average household organic waste generation observed during the final two months of the intervention period, after behavioral stabilization had been identified. To improve consistency, households received initial guidance regarding waste separation and weighing procedures before data collection began. The percentage reduction was calculated using the formula ((Baseline − Post) / Baseline) × 100. This procedure is consistent with household-level intervention studies on organic waste diversion (Trushna et al., 2024; Naujokas & Bobinaite, 2025). Behavioral changes were documented through observations of sorting consistency, use of processing methods, participation, and semi-structured interviews. Behavioral interpretation was informed by the Theory of Planned Behavior (Ajzen, 1991; Etim et al., 2024), particularly the dimensions of attitude, subjective norms, and perceived behavioral control. Triangulation between quantitative waste generation data and qualitative findings was applied to strengthen interpretative validity (Shadish et al., 2002; O'Cathain, 2020).

Quantitative analysis was conducted using pre-post pairwise comparisons by calculating the mean, standard deviation, 95% confidence interval of the difference in means, paired t-tests, Wilcoxon tests as a non-parametric robustness check, and effect sizes (Cohen's d for paired samples). Normality of the baseline distribution was tested using Shapiro–Wilk. Qualitative analysis was conducted through thematic coding of interview transcripts and field notes to identify patterns of behavioral consistency, enabling and inhibiting factors, and institutional strengthening dynamics. Repeated household-level monitoring, periodic observations over six months, and methodological triangulation were applied to enhance reliability and interpretative validity. Although repeated observations improved temporal consistency and reduced short-term observational bias, the absence of a control group limits definitive causal attribution.

Figure 2. Community empowerment intervention activities, including environmental education, decentralized composting training, eco-enzyme production, and biopore installation

3. Results

3.1 Baseline Condition of Household Organic Waste Generation

Prior to the implementation of the intervention, none of the participating households (n = 30) practiced systematic source separation of organic waste. All household waste was stored in mixed containers and disposed of through the routine municipal collection system without any form of on-site processing or pre-treatment. Organic and inorganic fractions were fully integrated into a single waste stream, reflecting a conventional linear "collect–transport–dispose" waste management model commonly observed in secondary urban contexts. Descriptive statistical analysis indicates that baseline household organic waste generation averaged 3.26 kg per household per day (SD = 0.63), with observed values ranging from 2.0 to 4.1 kg/day. The 95% confidence interval for the mean was 3.03–3.50 kg/day, suggesting a relatively precise estimation of the baseline organic waste load. The coefficient of variation (CV) was calculated at 19.32%, indicating moderate intra-community heterogeneity in waste generation across households within the same neighborhood cluster.

A Shapiro–Wilk normality test yielded W = 0.929 (p = 0.045), indicating a slight deviation from strict normality at the 5% significance level. However, given the sample size (n = 30), parametric procedures remain robust to minor departures from normality in accordance with the central limit theorem. The distribution did not exhibit extreme skewness or dispersion that would invalidate subsequent inferential analysis. In terms of composition, baseline organic waste primarily consisted of cooked food leftovers (rice and side dishes), vegetable residues, fruit peels, and moist kitchen preparation scraps. These materials were disposed of without prior drainage, volume reduction, or separation, thereby entering the municipal waste stream in a highly biodegradable and moisture-rich state. Such characteristics increase transport weight, accelerate decomposition processes, and potentially intensify downstream environmental burdens at final disposal facilities.

Importantly, no households reported engaging in composting, biopore infiltration systems, eco-enzyme production, or any other form of decentralized organic waste treatment prior to the intervention. Minor informal practices, such as occasional feeding of food scraps to animals, were negligible and did not materially affect the measured waste volumes. Thus, baseline conditions can be characterized as a fully mixed waste system with zero structured source-based reduction. From a systems perspective, the baseline data demonstrate that an average of 3.26 kg/day of biodegradable material per household was directly embedded within the municipal residual waste stream. In the absence of upstream diversion mechanisms, the entire organic fraction imposed a direct logistical and environmental burden on downstream municipal infrastructure. These baseline findings establish a robust empirical reference point for evaluating the measurable impact of the six-month community empowerment intervention.

3.2 Post-Intervention Changes in Household Organic Waste Generation

Following six months of community empowerment intervention, a substantial reduction in household organic waste entering the municipal collection system was observed. Post-intervention measurements indicate that average organic waste generation decreased to 1.56 kg per household per day (SD = 0.49), compared to the baseline mean of 3.26 kg/day (SD = 0.63). The mean reduction amounted to 1.71 kg per household per day, corresponding to a 52.30% decrease relative to baseline conditions. The 95% confidence interval for the mean difference was 1.50–1.91 kg/day, indicating a statistically precise and practically meaningful reduction in organic waste generation.

A paired-sample t-test confirmed that this reduction was highly significant, $t(29) = 16.78$, $p < 0.001$. The magnitude of the intervention effect was exceptionally large, with a Cohen's d of 3.06, indicating substantial and sustained behavioral change at the household level. To ensure robustness against potential deviations from normality, a Wilcoxon signed-rank test was also conducted, yielding consistent results ($p < 0.001$). The convergence of parametric and non-parametric findings strengthens the robustness of the observed reduction.

Table 1. Comparison of Household Organic Waste Generation Before and After the Intervention (n = 30)

Parameter	Baseline	Post-Intervention	Difference (Δ)
Mean (kg/day)	3.26	1.56	1.71
SD	0.63	0.49	0.56
Percentage Reduction	–	–	52.30%
95% CI of Δ (kg/day)	–	–	[1.50 ; 1.91]
Paired t-test	–	–	t(29) = 16.78
p-value	–	–	< 0.001
Cohen's d	–	–	3.06

Statistical Notes:

A paired-samples t*-test was conducted to compare household organic waste generation before and after the intervention (df = 29). The results indicate a statistically significant reduction (*$p < 0.001$*). The calculated effect size (Cohen's* d *= 3.06) suggests a large intervention effect according to conventional interpretation benchmarks. The 95% confidence interval of the mean difference indicates consistent reduction across participating households.*

The effect size observed in this study exceeds typical intervention magnitudes reported in community-based environmental behavior research, suggesting that the integration of environmental literacy, technological flexibility, and structured facilitation generated a synergistic impact rather than incremental behavioral adjustment. From a systems perspective, the reduction implies that more than half of the biodegradable fraction previously embedded in the municipal waste stream was effectively diverted and retained at the household level. This diversion reduces transport weight, moisture load within residual waste, and potential downstream environmental burdens associated with organic decomposition at final disposal facilities.

Importantly, the observed reduction was not driven by financial incentives or regulatory enforcement, but by sustained engagement, behavioral reinforcement, and locally embedded social support structures. The magnitude and statistical consistency of the reduction suggest that decentralized organic waste management may generate substantial system-level effects when supported by structured community empowerment mechanisms. Overall, the post-intervention findings provide robust empirical evidence that source-based organic waste diversion is both statistically significant and operationally scalable within secondary urban residential contexts.

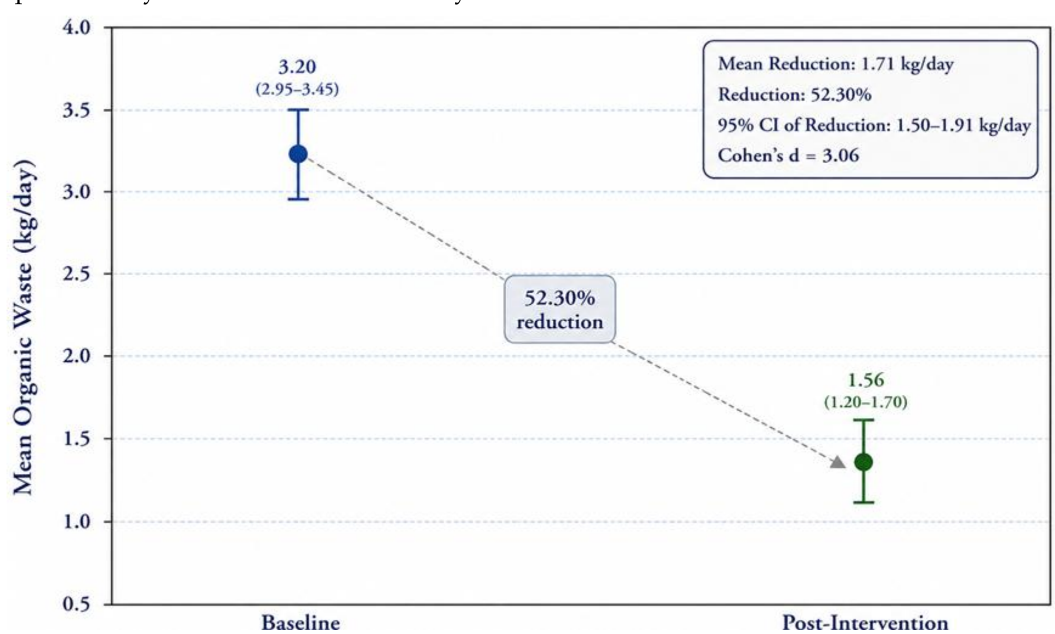

Figure 3. Mean Household Organic Waste Generation Before and After Intervention (95% CI)

3.3 Adoption of Organic Waste Treatment Methods

During the intervention period, households were given the flexibility to choose organic waste treatment methods based on available space, household capacity, and perceived ease of operation. This adaptive approach was deliberately designed to minimize resistance and accommodate differences within the community. Among the 30 participating households, 9 (30%) adopted biopore infiltration systems, another 9 (30%) implemented stacked bucket composting, 2 (6.7%) chose the Takakura composting method, 7 (23.3%) practiced eco-enzyme production, and 2 (6.7%) combined multiple methods. The distribution reflects a clear preference for low-cost, low-complexity options that require minimal technical skills and financial investment. No single method dominated, suggesting that contextual compatibility, rather than technological superiority, primarily shaped adoption decisions.

Biopore systems and stacked bucket composting together accounted for 60% of households, largely because they are simple to implement, require limited monitoring, incur negligible additional cost, and produce minimal odor when properly maintained. The Takakura method was adopted mainly by households with larger outdoor space and greater willingness to manage aeration and moisture more actively, which may explain its lower uptake. Eco-enzyme production was often used as a complementary method, typically combined with composting or biopore systems, and applied to smaller volumes of kitchen waste or as part of broader environmentally motivated practices.

The variation in method selection highlights the importance of technological flexibility in sustaining participation. By allowing households to align treatment options with their specific domestic conditions, the intervention reduced entry barriers and strengthened a sense of ownership. A small proportion of households (6.7%) adopted hybrid approaches, indicating adaptive optimization in response to practical experience. From a systemic perspective, the coexistence of multiple decentralized treatment methods demonstrates that effective source-based organic waste reduction does not require uniform technological standardization. Instead, contextual adaptability and perceived feasibility are central to sustained adoption. The intervention ultimately formed a decentralized network of small-scale treatment nodes distributed across households, reducing reliance on centralized infrastructure and enhancing resilience and scalability in secondary urban settings.

3.4 Behavioral Adaptation and Participation Dynamics

Beyond the statistically significant reduction in organic waste generation, the intervention produced measurable behavioral adaptation at the household level. The observed quantitative decline was accompanied by shifts in routine practices, social norms, and cognitive perceptions regarding waste management. These behavioral dimensions provide critical explanatory context for the magnitude and stability of the reduction effect.

3.4.1 Consistency of Source Separation

At the initial stage of implementation, approximately 60% of households consistently practiced source separation during the first month of intervention. Early inconsistencies were primarily associated with forgetfulness, uncertainty regarding waste categorization, and adjustment to newly introduced routines. By the fourth month, consistent separation behavior increased to more than 85% of participating households. At the end of the six-month intervention period, nearly all households demonstrated routine and stable separation practices, with only minor occasional lapses reported. This progressive improvement in behavioral consistency aligns temporally with the stabilization of waste reduction levels reported in Section 3.2. The convergence of increased adherence and quantitative reduction suggests a direct functional relationship between routine formation and diversion performance.

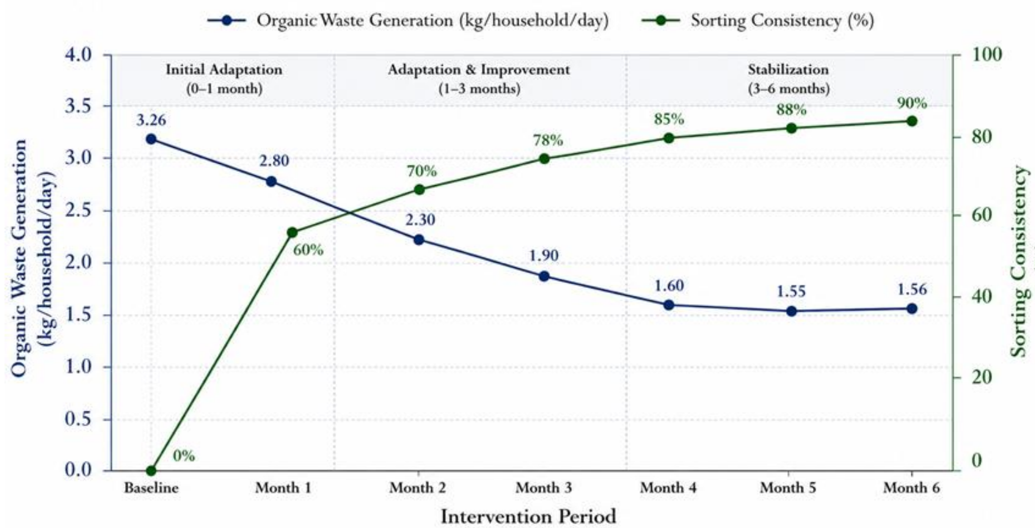

Figure 4. Indicative Time-Series Trend of Household Organic Waste Reduction and Source Separation Consistency During the Intervention Period

3.4.2 Internalization of Daily Practice

Qualitative observations and structured monitoring records indicate a transition from externally prompted behavior to internalized habitual practice. During the early weeks, several participants perceived organic waste processing as an additional domestic burden requiring extra effort. However, after approximately six to eight weeks, most households reported that separation and treatment activities had become integrated into normal kitchen routines. Participants frequently described the process as "automatic" or "habitual," indicating reduced cognitive load and diminished resistance. This internalization phase coincides with the statistically significant and sustained reduction in waste generation, suggesting that behavioral embedding played a decisive role in maintaining diversion outcomes.

3.4.3 Strengthening of Social Norms

The neighborhood administrative structure functioned as a social reinforcement mechanism throughout the intervention. Regular discussions, peer exchanges, and progress monitoring created a collective environment in which source separation became socially expected behavior rather than an individual choice. Importantly, reinforcement operated through encouragement and social modeling rather than coercion. Households reported increased motivation when observing neighboring participants successfully implementing treatment methods. This form of normative alignment contributed to behavioral stabilization and likely reduced the risk of relapse to pre-intervention practices.

3.4.4 Reduction of Initial Psychological Barriers

During the early implementation phase, concerns regarding potential odor, pest attraction, and operational complexity were expressed by several participants. These apprehensions represented psychological barriers to adoption. As practical experience accumulated, perceived difficulty declined substantially. Participants reported that proper management techniques mitigated odor and pest issues, and that procedural steps were simpler than initially anticipated. The decline in perceived barriers coincided with the 6–8 weeks adaptation period identified in Section 3.2, reinforcing the interpretation that behavioral stabilization required a structured transition phase rather than immediate compliance.

3.4.5 Integrated Interpretation

Taken together, these findings indicate that the reduction in organic waste generation cannot be attributed solely to technological adoption. Instead, the intervention facilitated a multi-layered behavioral adaptation encompassing cognitive awareness, habitual integration, and social reinforcement. Behavioral adaptation preceded and enabled stabilization of quantitative reduction outcomes. The alignment between increasing behavioral consistency and statistically significant waste diversion suggests that decentralized waste management success is strongly dependent on sustained social engagement and routine formation. In this study, the magnitude of reduction (Cohen's d = 3.06) reflects not only technical implementation but also deep behavioral embedding within daily household practices.

3.5 Stability of Behavioral and Waste Reduction Outcomes Over the Six-Month Period

Trend observations across the six-month intervention indicate that the reduction in household organic waste generation did not occur instantaneously but followed a gradual stabilization trajectory. During the first one to two months, fluctuations were observed as households adjusted to new separation and treatment routines. By the third month, waste volumes began to decline more consistently. From the fourth month onward, organic waste generation stabilized within a relatively narrow range around the post-intervention mean of 1.56 kg per household per day. Importantly, no rebound effect was detected during the final monitoring phase. Waste generation levels did not return toward baseline values after the initial reduction was achieved. This absence of regression suggests that the observed change was not merely a short-term response to facilitator presence or temporary enthusiasm, but reflected sustained behavioral consolidation.

The stability of outcomes corresponds with the 6–8 weeks adaptation period identified earlier. During this phase, separation practices transitioned from externally prompted behavior to normalized household routines. Once this internalization occurred, diversion performance remained consistent without intensified supervision. From an intervention evaluation perspective, temporal stability represents a critical threshold distinguishing temporary compliance from embedded behavioral change. The maintenance of reduced waste levels across the final two months strengthens the interpretation that the intervention achieved sustained behavioral stabilization rather than transient participation. These findings reinforce the consistency and durability of the observed reduction effect and support the durability of the community-based model under real-world conditions.

4. Discussion

4.1 Positioning of Findings within International Literature

The principal finding of this study demonstrates that a six-month community empowerment intervention produced a statistically robust reduction of 52.30% in household organic waste entering the municipal stream, equivalent to a mean decrease of 1.71 kg per household per day (95% CI: 1.50–1.91). The reduction was highly significant ($t(29) = 16.78$, $p < 0.001$) and characterized by an exceptionally large effect size (Cohen's $d = 3.06$), indicating substantial and sustained behavioral adaptation rather than incremental behavioral adjustment. This magnitude reinforces international evidence that source separation and decentralized organic waste treatment are among the most effective upstream strategies for reducing urban waste burdens (Zhang et al., 2024; Maletz et al., 2025). Global analyses of separate biowaste collection consistently highlight methane mitigation, reduced landfill dependency, and improved resource recovery as key benefits (Maletz et al., 2025). However, much of the existing literature operates either at macro-policy scale or within short-term experimental contexts. Medium-term empirical validation within real-world neighborhood settings remains comparatively limited.

The exceptionally large effect size observed in this study exceeds many intervention magnitudes reported in household waste separation research (Trushna et al., 2024; Moeini et al., 2023). This suggests that the reduction was not solely driven by informational exposure or isolated technological adoption, but by the structured integration of multiple reinforcing components. The 6–8 weeks adaptation trajectory observed before stabilization aligns with behavioral literature emphasizing repetition, reinforcement, and habit formation (Ajzen, 1991; Etim et al., 2024). From a technical perspective, the adoption of low-cost methods—biopore infiltration systems, stacked bucket composting, and Takakura composting—corroborates research indicating that decentralized composting is operationally feasible in infrastructure-constrained urban environments (Manea et al., 2024; Rao & Parsai, 2023; Oviedo et al., 2025). Nevertheless, international studies repeatedly caution that technological effectiveness depends on consistent source separation and sustained social engagement (Manea et al., 2024; Rao & Parsai, 2023). The present findings substantiate this argument: technology functioned as an enabling instrument, while the primary determinant of reduction was sustained behavioral stabilization embedded within local governance structures.

The role of the RT as a normative reinforcement and coordination node further aligns with literature on participatory governance and social learning (Zebua et al., 2025). Rather than serving as a passive administrative entity, the RT operationalized collective accountability and social reinforcement, reducing relapse risk and strengthening long-term behavioral consistency. By providing statistically validated, medium-term evidence from a secondary Indonesian city context—an underrepresented setting in global waste governance research—this study adds empirical depth to international discussions. The convergence of statistical rigor, behavioral stabilization, and institutional embedding demonstrates that participatory waste governance can generate measurable environmental outcomes.

4.2 Policy Implications for Secondary Cities

The findings of this study have important implications for secondary cities that often face fiscal constraints, limited transport fleets, and increasing pressure on landfill capacity. The observed 52.30% reduction demonstrates that upstream, source-based interventions can significantly decrease municipal waste burdens before waste even enters the transport system. Compared to capital-intensive downstream solutions—such as expanding vehicle fleets or constructing additional landfill cells—household-level diversion reduces both volume and weight at the point of origin. Moreover, the intervention model is inherently low-cost and scalable. Because it relies primarily on behavioral facilitation, simple treatment technologies, and local institutional coordination rather than centralized infrastructure, it offers practical feasibility for small and medium-sized cities. Technical–economic assessments of decentralized composting systems indicate that such approaches may be more cost-efficient than expanding centralized treatment capacity (Oviedo et al., 2025), and the empirical reduction documented in this study supports that argument.

From an implementation perspective, the intervention required relatively low household-level costs because most treatment methods utilized inexpensive and locally available materials. Simple systems such as stacked bucket composters and biopore infiltration holes could generally be implemented at approximately IDR 150,000 per unit and IDR 100,000 per point, respectively, with most participating households requiring only one unit of each system. Compared to the substantial capital requirements associated with centralized waste transport expansion or landfill development, these decentralized approaches represent a financially accessible alternative for secondary cities with limited fiscal capacity. Although a formal cost–benefit analysis was beyond the scope of this study, the observed reduction suggests potential operational savings through decreased transport loads, lower landfill dependency, and reduced downstream waste management pressure.

The results also suggest the need for a broader paradigm shift from logistics-oriented waste governance toward a behavior-centered framework. Given that organic waste constitutes a substantial proportion of municipal waste streams (Zhang et al., 2024; Maletz et al., 2025), addressing this fraction at the source may generate greater systemic impact than incremental improvements in collection efficiency alone. This finding is consistent with previous studies emphasizing that sustainable waste management performance depends not only on infrastructure expansion but also on community participation, social learning, and behavioral adaptation (Trushna et al., 2024; Moeini et al., 2023; Zebua et al., 2025). In addition, the intervention aligns with circular economy objectives and national waste reduction targets, as household-level organic diversion supports resource recovery while mitigating methane emissions from landfill decomposition (Scharff et al., 2023; Ramzy et al., 2025). Previous studies have also demonstrated that decentralized organic waste treatment contributes to landfill diversion and environmental impact reduction through localized material recovery processes (Manea et al., 2024; Rao & Parsai, 2023). If implemented at broader scale, reductions of similar magnitude could potentially extend landfill lifespan and reduce greenhouse gas emissions. However, the scalability of such interventions remains dependent on continuous facilitation, institutional commitment, and contextual adaptation at the neighborhood level (Leknoi et al., 2024; Naujokas & Bobinaite, 2025).

Finally, community empowerment initiatives should be formally integrated into municipal planning frameworks rather than treated as short-term awareness campaigns. Institutionalizing such programs within official waste management strategies would strengthen continuity, ensure more stable resource allocation, and improve interdepartmental coordination. The integration of local community structures into municipal waste governance may also strengthen long-term program sustainability by embedding environmental practices within existing social institutions (Zebua et al., 2025; Leknoi et al., 2024).

4.3 Theoretical Advancement: A Four-Layer Socio-Technical Micro-Governance Model

While prior sections described the empirical components of the intervention, the present findings enable a more explicit theoretical articulation. This study advances a four-layer socio-technical micro-governance model that extends behavior-centered waste management frameworks by integrating cognitive, technological, reinforcement, and institutional dimensions into a single interactive architecture. Conventional applications of the Theory of Planned Behavior explain household waste separation primarily through attitudes, subjective norms, and perceived behavioral control (Ajzen, 1991; Etim et al., 2024). Although TPB provides a useful predictive lens, it does not fully account for stabilization mechanisms required for sustained behavioral adaptation. Previous studies have largely examined behavioral determinants at the individual level, while less attention has been given to how neighborhood institutions and repeated facilitation processes sustain behavioral continuity over time (Trushna et al., 2024; Moeini et al., 2023; Zebua et al., 2025). The present study demonstrates that cognitive alignment alone is insufficient. Instead, durable waste reduction emerges from the interaction between behavioral intention and institutional embedding.

At the foundational level, environmental literacy operates as a cognitive activation mechanism. It reshapes attitudes and normative perceptions, aligning household motivation with environmental objectives. However, literacy functions only as an enabling condition. Without operational feasibility and reinforcement, behavioral intentions risk weakening over time. This finding supports previous intervention studies emphasizing that environmental education alone is insufficient without continuous engagement and contextualized implementation mechanisms (Trushna et al., 2024; Moeini et al., 2023).

The second layer—contextualized simple technologies—translates intention into feasible action. By offering flexible, low-cost treatment options, the intervention enhanced perceived behavioral control while minimizing structural barriers. Technological flexibility thus acts as a mediator between intention and execution, reducing friction between motivation and practice. The use of simple decentralized treatment technologies also aligns with studies highlighting the operational suitability of low-cost household composting systems in developing urban settings (Manea et al., 2024; Rao & Parsai, 2023; Oviedo et al., 2025).

The third layer—repeated facilitation and monitoring—introduces a temporal stabilization mechanism. Behavioral theory acknowledges the role of repetition in habit formation, yet empirical waste governance literature rarely documents the adaptation phase required for consolidation. The observed 6–8 weeks transition period in this study illustrates that reinforcement is not auxiliary but essential for behavioral stabilization. Facilitation bridges the gap between short-term compliance and habitual integration. This observation reinforces findings from behavioral intervention literature indicating that repeated interaction and social reinforcement are important factors in sustaining pro-environmental practices (Moeini et al., 2023; Naujokas & Bobinaite, 2025).

The fourth layer—local institutional embedding through the RT structure—constitutes the primary theoretical extension offered by this study. Existing behavioral models emphasize subjective norms but treat them largely as perceptual constructs. In contrast, this intervention demonstrates that norms can be institutionally embedded within neighborhood-level governance units, transforming individual practice into socially stabilized behavior. Institutional anchoring reduces relapse probability by converting voluntary action into socially reinforced routine. This moves beyond attitudinal influence toward micro-governance stabilization. The findings therefore extend participatory governance perspectives by demonstrating how local social institutions function not merely as facilitators, but as stabilizing governance mechanisms for decentralized environmental management (Zebua et al., 2025; Leknoi et al., 2024).

The interaction among these four layers forms a non-linear, mutually reinforcing system rather than a sequential intervention pathway. Literacy activates intention; technological flexibility enables execution; facilitation stabilizes repetition; and institutional embedding anchors durability. The exceptionally large effect size ($d = 3.06$) suggests that system-level alignment across these dimensions generates synergistic rather than merely additive impacts. This indicates that the effectiveness of community-based organic waste reduction may depend less on isolated technical interventions and more on the integration between behavioral, technological, and institutional dimensions within local governance systems.

The central theoretical contribution of this study lies in reframing decentralized organic waste management as a governance-centered socio-technical system. Instead of positioning composting merely as a technical solution, the model conceptualizes household waste diversion as an embedded micro-governance process operating within neighborhood institutions. This perspective integrates behavioral theory with participatory governance literature (Zebua et al., 2025) and demonstrates how institutional reinforcement transforms individual pro-environmental behavior into collective environmental performance. Accordingly, the study contributes to expanding decentralized waste management discourse from infrastructure-oriented approaches toward socio-technical governance frameworks emphasizing long-term behavioral sustainability and local institutional resilience.

4.4 Limitations and Future Research

Although the findings are statistically robust, several limitations should be acknowledged. The study was conducted within a single neighborhood cluster ($n = 30$), which supports robust within-group comparison due to the paired design and large effect size, but limits broader generalizability. Replication across multiple neighborhoods with diverse socio-economic conditions is therefore necessary to evaluate scalability and contextual applicability. The monitoring period was restricted to six months; although behavioral stabilization was observed during the final two months, the long-term sustainability of behavioral adaptation beyond the intervention period remains uncertain and would benefit from longitudinal observation over 12–24 months.

In addition, environmental impact indicators—such as greenhouse gas mitigation, avoided transport emissions, or life-cycle performance—were not directly quantified. The individual causal contribution of each component within the four-layer empowerment model was not statistically modelled, and the absence of a control group limits definitive causal attribution despite the strong pre–post effect observed in this study. A comprehensive cost–benefit analysis was also beyond the scope of the present research. Future studies should therefore focus on multi-site replication, longer-term evaluation, integrated environmental impact assessment, causal modelling of empowerment mechanisms, and economic feasibility analysis to strengthen the empirical and policy foundations of community-based organic waste governance in secondary urban contexts.

5. Conclusion

This study demonstrates that a structured six-month community empowerment intervention can produce a statistically robust and practically meaningful reduction in household organic waste generation. The intervention achieved a 52.30% decrease in organic waste entering the municipal stream, corresponding to a mean reduction of 1.71 kg per household per day (95% CI: 1.50–1.91), with an exceptionally large effect size (Cohen's $d = 3.06$). These results indicate sustained behavioral adaptation and routine integration throughout the intervention period. The findings confirm that effective source-based organic waste reduction is not driven by technology alone. Instead, measurable and stable outcomes emerge from the alignment of four interdependent components: environmental literacy, contextualized simple technologies, repeated facilitation, and local institutional embedding. The interaction among these layers created a decentralized network of household-level micro-treatment nodes, reducing dependence on downstream municipal logistics and landfill disposal.

Conceptually, this research advances a socio-technical micro-governance model for organic waste management tailored to secondary urban contexts. It bridges technical composting approaches with participatory governance structures and demonstrates their combined contribution through statistically supported empirical findings. By showing that community empowerment can generate measurable environmental outcomes within infrastructure-constrained environments, the study reframes upstream waste reduction as a foundational component of sustainable urban governance rather than merely a supplementary awareness activity. For secondary cities facing fiscal limitations and increasing waste pressures, the findings suggest that behavior-centered, decentralized strategies may offer broader systemic benefits than infrastructure expansion alone. If implemented more broadly, reductions of similar magnitude could contribute to lowering municipal transport loads, reducing landfill pressure, and mitigating associated environmental risks.

Ultimately, the study demonstrates that sustainable waste governance begins at the household level but is stabilized through collective institutional reinforcement. The integration of social processes and practical technologies represents the central innovation of this research and provides a replicable framework for community-based organic waste reduction in emerging urban systems.

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