International Journal of Sustainable Development and Planning
Vol. 21, No. 9, September, 2026, pp. 4113-4133
Journal homepage: http://iieta.org/journals/ijsdp

From Bins to Benefits: How Layered Interventions Shape Household Waste-Sorting Behavior in Indonesia

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https://doi.org/10.18280/ijsdp.210914

Received: 16 July 2026
Revised: 15 September 2026
Accepted: 22 September 2026
Available online: 30 September 2026

Keywords:
attitude, behavior, circular economy, field experiment, household waste-sorting, monetary incentive, urban Indonesia

ABSTRACT

Household waste sorting is a critical upstream activity for improving recycling performance and supporting the transition toward a circular economy. However, evidence from Indonesia regarding the effectiveness of household-level behavioral interventions remains limited. This study evaluates household responses to progressively layered waste-sorting interventions in urban residential areas of Depok and South Tangerang, Indonesia. A stratified, four-arm field experiment with repeated daily household observations was employed. Forty households were stratified by socioeconomic status and allocated to one control arm and three treatment arms, with 10 households in each arm. Each household was observed daily for 10 consecutive days, generating 400 household-day observations. Treatment 1 provided waste-sorting facilities; Treatment 2 combined the facilities with scheduled collection services and practical sorting information; and Treatment 3 added monetary incentives for eligible recyclable materials. pooled ordinary least squares (pooled OLS) and random effects panel regressions were used to compare the intervention arms with the control while adjusting for household, housing, socioeconomic, and waste-service characteristics. Across model specifications, households assigned to the three intervention arms exhibited higher quantities of sorted inorganic waste than the control group. Treatment 3 showed the largest adjusted difference, followed by Treatment 1 and Treatment 2. These findings suggest that practical convenience, sorting capability, service support, and economic motivation jointly shape household waste-sorting behavior and support the use of integrated, context-sensitive interventions for advancing circular-economy objectives.

1. INTRODUCTION

As a developing country, Indonesia continues to face significant challenges in solid waste management. Natural population growth, urbanization, and increasing economic activity are among the key factors contributing to the rising volume of municipal solid waste [1-3], which is projected globally to reach 2 billion tons per year and increase by 56% by 2050 [4]. According to the Ministry of Environment [5], Indonesia, with a population exceeding 280 million in 2025 [6], generated at least 31.62 million tons of waste during that year (based on reports from 291 regencies/cities). The waste composition was dominated by food waste (40.61%), followed by plastic (20.53%), wood and yard (13.22%), paper and cardboard (11.38%), metals (3.03%), textiles (2.52%), glass (2.36%), rubber and leather (2.01%), and other types (6.77%). The same report indicates that households accounted for the largest share of waste generation (57.83%), followed by markets and commercial activities (19.96%), while the rest originated from public facilities, offices, and other sectors. Inadequate waste management poses serious risks to environmental quality and public health [3, 7, 8].

Like many other countries that have invested in waste management infrastructure and environmental campaigns [9, 10], Indonesia has undertaken considerable efforts to improve its waste management system. Nevertheless, by 2025 only 32.76% of the total national waste had been properly managed, with merely 32.44% disposed of through controlled sanitary

management, while the remaining 67.56% was still handled through open dumping at final disposal sites. Indonesia's waste management policy is primarily governed by Law No. 18 of 2008 on Waste Management, which regulates waste reduction through waste prevention, recycling, and reuse, as well as waste handling through sorting, collection, transportation, treatment, and final disposal. One of the implementing regulations is Government Regulation No. 81 of 2012 on Household Waste Management and Household-like Waste Management, which provides detailed guidelines for waste reduction and handling, including waste sorting, collection, transportation, treatment, and final disposal. The regulation also stipulates that household waste management up to the temporary collection point, which is generally located near residential areas, is the responsibility of individual households. Consequently, household participation and the active involvement of family members are essential to the success of waste management initiatives.

However, infrastructure development and regulatory measures alone have proven insufficient to encourage public participation in waste management [11]. Research conducted in South Africa found that effective waste management cannot rely solely on physical infrastructure such as landfills, recycling facilities, or waste treatment technologies [12]. Similarly, another study demonstrated that the introduction of technology to support a door-to-door waste sorting system in Hungary unexpectedly stimulated more consumerist behavior, as people perceived additional consumption as acceptable as long as waste could be recycled [13]. Even Germany, which possesses one of the world's most advanced waste management systems, continues to experience frequent waste sorting errors due to residents' lack of knowledge [4]. Other studies further argue that policy directives and public appeals alone are insufficient. For example, despite the implementation of policies promoting single-use plastic reduction, waste banks, and circular economy programs, public participation in waste sorting, waste reduction, and the use of recycled products remains relatively low in Indonesia [14]. Asih et al. [15] argued that no single policy is universally effective. Their findings demonstrate that the most effective interventions consist of a combination of environmental education, economic instruments, and the provision of appropriate facilities tailored to the socio-economic characteristics of local communities.

The existing literature suggests that social factors, including public perceptions, behaviors, preferences, and participation, significantly influence the success of waste management policies [16, 17]. Individual socio-demographic characteristics such as gender, age, household size, income level, shopping frequency, habits, and skills have all been shown to correlate with household waste management behavior [18-20]. Consequently, many studies argue that improving environmental knowledge and awareness is crucial for achieving successful waste management, particularly within a circular economy framework that relies heavily on the recovery and reuse of valuable waste materials. A literature review by Etim et al. [21] concluded that waste management policies should be designed using a context-sensitive approach that considers cultural values, institutional arrangements, public trust, and local government capacity. Furthermore, Napitupulu and Muhyidin [22] emphasized that successful waste management depends on cross-sectoral collaboration and behavioral change rather than purely technical solutions. A recent Indonesian study found that both monetary incentives and environmental information nudges can improve household waste sorting behavior, although they produce different behavioral effects [20]. The study demonstrated that waste sorting behavior is influenced by a combination of extrinsic motivation (economic incentives) and intrinsic motivation (environmental awareness). Price incentives are effective in generating rapid behavioral change by increasing perceived economic benefits, but their effects tend to diminish once the incentives are withdrawn. In contrast, environmental messages produce slower behavioral changes but are more effective in strengthening social norms and intrinsic motivation, resulting in more persistent long-term effects.

Compared with studies conducted in other countries, where behavioral interventions based on economic incentives and environmental awareness are frequently designed using the Theory of Planned Behavior (TPB**)** framework [3, 23-25], experimental studies of this nature remain relatively limited in Indonesia. This study therefore aims to fill the gap by providing both empirical and experimental evidence regarding household waste sorting behavior. Specifically, it will examine community responses to several intervention strategies across three socio-economic groups by manipulating key determinants of waste sorting behavior, namely the provision of waste sorting facilities, waste collection methods, and monetary incentives. These interventions are intended to identify the determinants that maximize public participation in supporting the circular economy. The objectives of this study are to evaluate the effectiveness and efficiency of each intervention in reducing the amount of mixed waste and increasing the quantity of properly sorted waste. Furthermore, the study will investigate socio-demographic and individual factors that may influence people's willingness and ability to sort household waste, including gender, educational attainment, income level, and other individual characteristics.

2. LITERATURE REVIEW

Waste sorting at source has been recognized as one of the most fundamental stages in urban waste management systems because it determines the effectiveness of subsequent management processes, from collection, recycling, composting, resource recovery, and final disposal. Waste sorting at source allows for the separation of materials with economic value, such as recyclable organic and inorganic waste, before they are mixed with other types of waste. This maintains material quality, increases recycling rates, reduces the amount of waste sent to landfills, and enhances resource reuse within a circular economy [1, 26]. The urgency of waste sorting is growing in developing countries, including Indonesia, which still faces various limitations in urban waste management systems. Population growth, rapid urbanization, and increasing consumption patterns have caused waste generation to increase faster than the capacity of existing management systems [1, 2]. Although the government has encouraged the implementation of a circular economy and increased resource reuse, most household waste is still disposed of mixed. This reduces the efficiency of recycling processes, reduces the quality of recoverable materials, and increases reliance on landfills as the final destination for waste management.

The importance of waste sorting is not only related to the technical aspects of waste management, but also a key prerequisite for realizing a circular economy. Sorting at source

allows materials to maintain good quality, making them easier to recycle, reducing environmental pollution, increasing resource utilization efficiency, and improving the economic viability of material recovery systems [26, 27]. In addition, various studies in Indonesia show that areas that implement community-based waste sorting programs have higher resource recovery rates than areas that only rely on conventional waste collection systems [1].

Although the benefits of waste sorting have been widely recognized, encouraging people to do so consistently remains a major challenge. Various studies have shown that waste sorting behavior is influenced not only by environmental awareness but also by socioeconomic conditions, institutional support, infrastructure availability, and various forms of behavioral intervention [11, 15]. Recent literature shows that increased knowledge and positive attitudes toward the environment are not necessarily followed by real behavioral changes. Various studies have found intention-behavior gaps, knowledge-action gaps, and attitude-behavior gaps, indicating that people with high environmental knowledge and awareness do not necessarily consistently separate waste in their daily lives [8, 17, 25]. Therefore, various studies have concluded that the success of waste sorting programs requires a combination of behavioral interventions, economic instruments, and institutional support.

Educational programs have been shown to increase public knowledge and awareness, but often fail to produce sustainable behavioral changes when implemented in isolation [15]. On the other hand, providing economic incentives can encourage behavioral change relatively quickly, although the impact tends to diminish once the incentives are stopped [20]. Meanwhile, the delivery of environmental information, the formation of social norms, and the strengthening of community ties have been proven to produce more lasting behavioral changes because they are able to strengthen people's intrinsic motivation [11, 20]. In addition to behavioral factors, the existence of infrastructure such as a separate waste collection system, waste banks, recycling facilities, and community-based waste management organizations also plays a role as supporting factors that enable the community to implement real waste sorting behavior [1, 21].

Evidence from developed countries underscores the importance of service design and continuity. In Catalonia, the introduction of door-to-door collection combined with mandatory separation increased the proportion of plastic packaging collected separately [28]. Brewer and Cameron [29] reached a related conclusion in their analysis of the temporary suspension of glass and plastic collection in New York City. Recycling declined sharply while the service was unavailable but recovered after collection resumed. Taken together, these studies suggest that convenient and dependable services can reinforce recycling practices, while disruptions may quickly weaken participation.

The picture is less straightforward in developing-country settings. Nepal et al. [30] found that information campaigns and the provision of public waste bins encouraged households to use formal collection services and improved perceptions of neighborhood cleanliness, but did not lead to a significant increase in source separation. A key explanation was that waste separated by households was later mixed again during collection. This finding is important because it shows that household-level efforts are unlikely to be sustained when the downstream system does not preserve separated waste streams. Households may have little reason to continue sorting when they see that their efforts do not produce a visible environmental outcome.

Studies from Indonesia point to a similar interaction between individual behavior and structural conditions. Sembiring et al. [31] found that color-coded bins were more useful when they were accompanied by clear labels, visual instructions, and direct communication. Containers alone did not guarantee correct sorting because household members were not always certain which categories particular materials should be placed in. Research in Balikpapan and Banyuwangi likewise reported a persistent gap between environmental knowledge and actual practice. Although many respondents understood the environmental consequences of plastic waste and expressed favorable attitudes towards waste management, participation in sorting and recycling remained limited, particularly where facilities and convenient services were lacking [8, 17].

These findings illustrate a recurring problem in the waste-behavior literature: awareness does not automatically lead to action. People may recognize the importance of waste separation while still finding the activity inconvenient, time-consuming, confusing, or economically unrewarding. Zhang's [23] systematic review therefore cautions against explaining waste separation solely through intention-based models. Attitudes and intentions matter, but their influence depends on whether households have the opportunity and ability to act. Facilities, collection arrangements, social norms, economic incentives, regulatory support, and institutional credibility all affect whether environmental intentions are translated into everyday practice.

Numerous studies have identified factors influencing waste sorting behavior; however, most of these studies focus on identifying behavioral determinants through cross-sectional surveys, behavioral models, or correlational analysis. These approaches are able to explain the relationships between variables, but they cannot yet robustly identify the causal influence of a program or intervention on behavioral change or improved waste management performance. Moreover, experimental research in Indonesia remains largely limited to evaluating the effectiveness of specific incentives or nudging methods, yielding relatively sparse empirical evidence on the effectiveness of waste sorting programs in the context of public policy [20].

The need to consider context is particularly evident in Indonesia. Voronkova et al. [11] showed that waste-management behavior in coastal communities is associated not only with infrastructure, but also with environmental concern and attachment to the local community. Frigo et al. [1] similarly demonstrated that plastic-waste flows differ across neighborhoods according to local leadership, socioeconomic conditions, infrastructure, community sorting programs, and the presence of informal waste actors. These studies suggest that household waste policy cannot be treated as a standardized intervention that will produce the same outcome in every community. The same program may work differently depending on service quality, housing conditions, local institutions, and access to markets for recyclable materials.

Despite this growing body of evidence, an important gap remains. Facilities, education, service design, and economic incentives have often been studied separately, or compared in pairs. As a result, the literature provides only limited insight into how these instruments work when they are introduced as successive components of the same policy package. It is still unclear whether providing sorting facilities is sufficient to

change behavior, whether education adds meaningful value once facilities are available, and whether economic incentives produce further improvement after households have already received both physical support and practical information.

A second limitation concerns the way household behaviour is commonly assessed. Many studies rely on self-reported knowledge, attitudes, intentions, willingness to participate, or willingness to pay. These measures are useful for understanding perceptions, but they do not necessarily reflect what households actually do. The knowledge–action and attitude–behavior gaps suggest that positive responses in a questionnaire may coexist with inconsistent or inaccurate sorting practices. Therefore, there is a need for research that places greater emphasis on observable behavior and on the actual outcomes of household waste separation.

Against this background, the present study evaluates household responses to three progressively layered waste-sorting interventions using a stratified four-arm field experiment with repeated daily observations. Unlike studies relying primarily on self-reported intentions or cross-sectional associations, this study uses directly measured household waste outcomes. The empirical analysis applies pooled ordinary least squares (pooled OLS) and random effects panel regressions to compare households assigned to the three intervention arms with those in the control arm while accounting for observed household, housing, socioeconomic, and waste-service characteristics. Because only one pre-intervention observation was available, the analysis is not specified as a Difference-in-Differences design and does not rely on a parallel-trends assumption. The study therefore focuses on adjusted differences in observed sorting outcomes across experimental arms during the study period.

3. METHODOLOGY

This study employed a stratified, parallel-arm field experiment combined with a short household-level panel design to examine household responses to three progressively layered waste-sorting interventions. The study was conducted in urban residential areas of Depok and South Tangerang (Figure 1), Indonesia. The study locations were selected based on regulatory approval, operational feasibility, accessibility for daily waste measurement, and comparability of neighborhood characteristics.

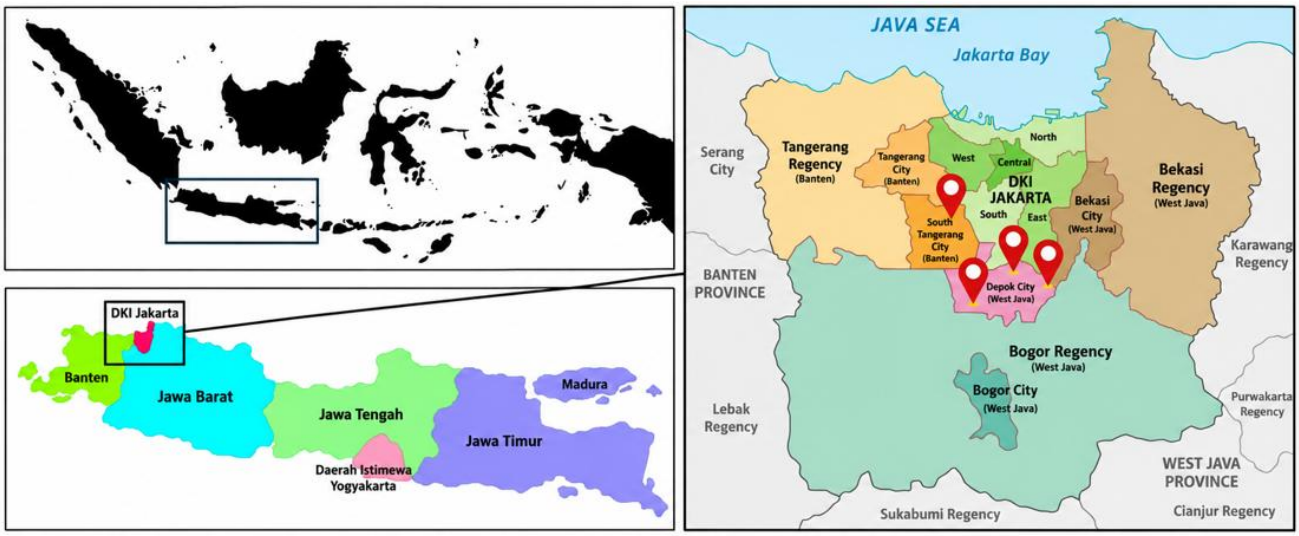


Figure 1. Research location

The household was the unit of analysis. A total of 40 households participated in the study. Households were classified into two socioeconomic strata and allocated across four experimental arms: one control arm and three treatment arms. Within each socioeconomic stratum, five households were included in each experimental arm. Consequently, each arm consisted of 10 households, yielding 40 households in total. This stratification was used to improve socioeconomic balance across the experimental arms and to account for potential differences in household waste-generation and sorting patterns.

The study used a between-household parallel-arm design. Each participating household remained in the same experimental arm throughout the study and did not receive the other treatment packages. The control group received no intervention. Treatment 1 provided households with waste-sorting facilities, particularly separate containers for recyclable and residual waste. Treatment 2 included the sorting facilities provided under Treatment 1 and added scheduled waste-collection services and practical information on waste-sorting procedures. Treatment 3 included all components of Treatment 2 and additionally provided monetary incentives through the purchase of eligible sorted recyclable materials.

Each household was observed daily for 10 consecutive days. Day 1 was used as the pre-intervention baseline observation. The assigned interventions were implemented during Days 2-9. On Day 10, the interventions were withdrawn to obtain an initial indication of household behavior immediately following treatment removal. With 40 households observed for 10 days, the study generated a balanced panel of 400 household-day observations. Repeated daily observations were used to capture short-term within-household variation in waste-sorting outcomes and to improve measurement precision relative to a single cross-sectional observation [32].

Waste sampling, weighing, and classification will follow SNI 19-3964-1994 [33] concerning the method for sampling and measuring municipal waste generation and composition. Trained field staff will collect and weigh separated recyclable

waste and residual or mixed waste from each participating household every day. A standardized field protocol, calibrated digital scales, labelled collection bags, and daily quality-control checks will be used to minimize measurement error. The primary outcome is the household recycling separation rate, defined as the weight of correctly sorted recyclable waste divided by total household waste generated on a given day. This ratio provides a directly interpretable measure of sorting performance and normalizes the outcome for variation in household waste volume. Secondary outcomes include: (i) residual mixed waste per capita, measured in kilograms per person per day; (ii) recyclable waste collected per capita; (iii) total waste generation per capita; and (iv) contamination of the recyclable fraction, expressed as the share of incorrectly sorted material. Behavioral intervention research indicates that convenience, information, service design, and economic incentives can influence participation in source separation, although their effectiveness depends on local implementation and household characteristics [34].

In the model, Y_{it} represents the waste-sorting outcome of household i on day t. $T1_i$, $T2_i$ and $T3_i$ indicate household assignment to Treatment Groups 1, 2, and 3, respectively, with the control group serving as the reference category. Because each household remained in the same experimental arm throughout the study, these treatment indicators vary across household but not overtime. Accordingly, β_1, β_2, and β_3 capture the adjusted differences in waste-sorting outcomes between each treatment group and the control group. Day fixed effects, represented by γ_t, account for daily variation common to all households, while X_{it} represents the vector of included control variables. The household-specific random effects, u_i, capture time-invariant unobserved heterogeneity across households, whereas ε_{it} represents the idiosyncratic error term.

$$Y_{it} = \alpha_i + \gamma_t + \beta_1 T1_{it} + \beta_2 T2_{it} + \beta_3 T3_{it} + \gamma X_{it} + \varepsilon_{it} \quad (1)$$

The static panel specification is estimated using two distinct regression techniques to ensure the statistical validity and robustness of the empirical findings:

a. Pooled OLS regression

The pooled OLS framework serves as a restrictive baseline model. It treats the data as a broad cross-section by pooling observations across both households and time, assuming that individual-specific effects are homogeneous.

b. Random effects regression

To address potential unobserved household-specific heterogeneity, a random effects model is deployed, in which α_i is treated as a random household-specific component of the composite error term rather than as a fixed parameter to be estimated. This specification is preferred to household fixed effects because the treatment assignment and most household characteristics remain time-invariant throughout the observation period. A fixed-effects transformation would absorb these variables and, crucially, prevent separate identification of the treatment effects because each household remained in the same experimental arm. Random effects retain the between-household variation required to estimate these coefficients, while the experimental allocation of households within predefined socioeconomic strata supports the assumption that household-specific effects are uncorrelated with treatment assignments. The choice between pooled OLS and random effects is then assessed using the Breusch-Pagan Lagrange Multiplier Test. The test is conducted to examine whether significant household-level variance exists, thereby determining whether random effects are preferable to pooled OLS.

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1 Household waste-sorting behavior following the interventions

Despite the implementation of waste-sorting interventions, the control group recorded the highest amount of recyclable waste sorted per capita (0.573 kg), exceeding both the overall sample average (0.459 kg) and all treatment groups (Figure 2).

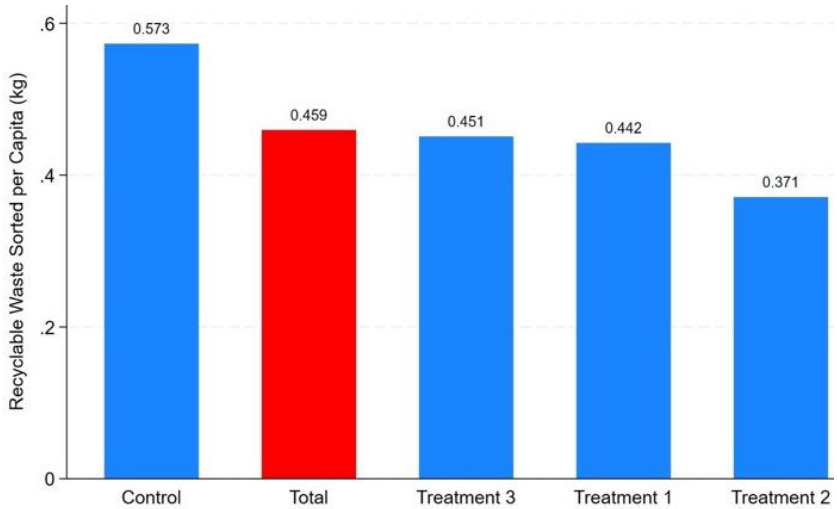


Figure 2. Average recyclable waste (kg) per capita across control and treatment groups

Among the interventions, Treatment 3 achieved the highest level of sorted recyclable waste (0.451 kg per capita), followed by Treatment 1 (0.442 kg), while Treatment 2 produced the lowest value (0.371 kg). This pattern suggests that households in the control group may have already exhibited relatively strong waste-sorting practices before the intervention, or that behavioral responses to the treatments had not yet fully materialized during the observation period. Nevertheless, the

variation across treatment groups points to heterogeneous intervention effects, with Treatment 3 appearing more effective in encouraging waste-sorting behavior than Treatment 1 and, particularly, Treatment 2.

A similar pattern emerges when examining inorganic waste generation per capita. The control group produced the largest volume of inorganic waste (0.292 kg per capita), substantially exceeding both the sample average (0.173 kg per capita) and all treatment groups (Figure 3).

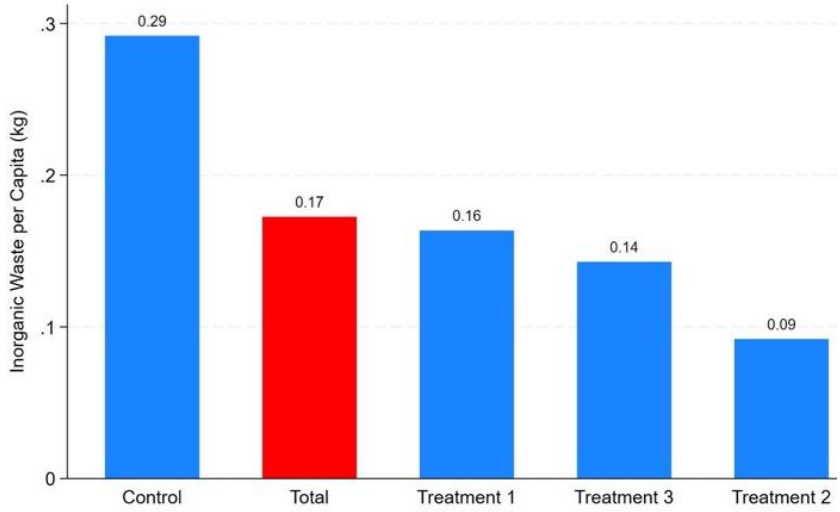


Figure 3. Average inorganic waste (kg) per capita across control and treatment groups

Among the interventions, Treatment 1 generated the highest amount of inorganic waste (0.163 kg per capita), followed by Treatment 3 (0.143 kg per capita), while Treatment 2 recorded the lowest level (0.092 kg per capita). This pattern mirrors the distribution observed for sorted recyclable waste, suggesting that lower recycling outcomes among the treatment groups may partly reflect a smaller amount of inorganic waste available for sorting rather than weaker sorting behavior itself. In particular, the notably lower inorganic waste generation observed in Treatment 2 points to possible differences in household consumption patterns or baseline characteristics.

Waste disposal practices were generally similar across the sample, with daily disposal emerging as the dominant behavior among households. Approximately 75% of households reported disposing of waste every day, while the remaining 25% disposed of waste two to three times per week. The prevalence of daily disposal was particularly pronounced in Treatment 1, where all households reported disposing of waste on a daily basis, compared with 80% and 70% in Treatment 2 and Treatment 3, respectively (Figure 4).

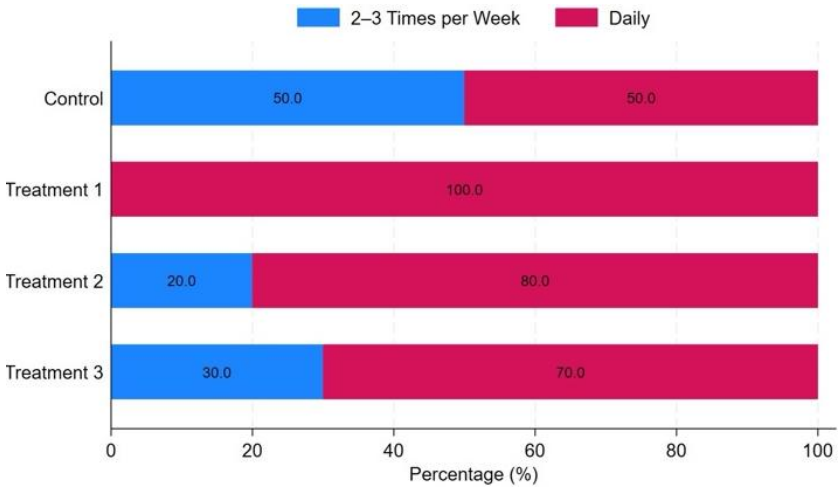


Figure 4. Distribution of waste disposal or collection frequency across groups

In contrast, the control group exhibited a more balanced pattern, with only half of households disposing of waste daily and the remainder reporting disposal frequencies of two to three times per week. These differences suggest that households receiving the interventions interacted with their waste more frequently than those in the control group, potentially affecting the volume of recyclable materials available for sorting. Variation in disposal frequency may partly contribute to the differences in waste-sorting outcomes observed across groups and should therefore be considered in subsequent econometric analyses.

A clear socioeconomic gradient is observed in the amount of recyclable waste sorted by households. Households in the lower economic stratum generated an average of 0.551 kg of sorted recyclable waste per capita, exceeding both the sample average (0.458 kg per capita) and the corresponding figure for households in the upper-middle stratum (0.364 kg per capita) (Figure 5).

The approximately 34% difference between the two groups suggests that recycling outcomes are closely associated with household socioeconomic characteristics. This pattern may reflect differences in consumption behavior, waste generation profiles, or the perceived economic value of recyclable materials, highlighting the importance of controlling for socioeconomic status when assessing the effectiveness of the waste-sorting interventions.

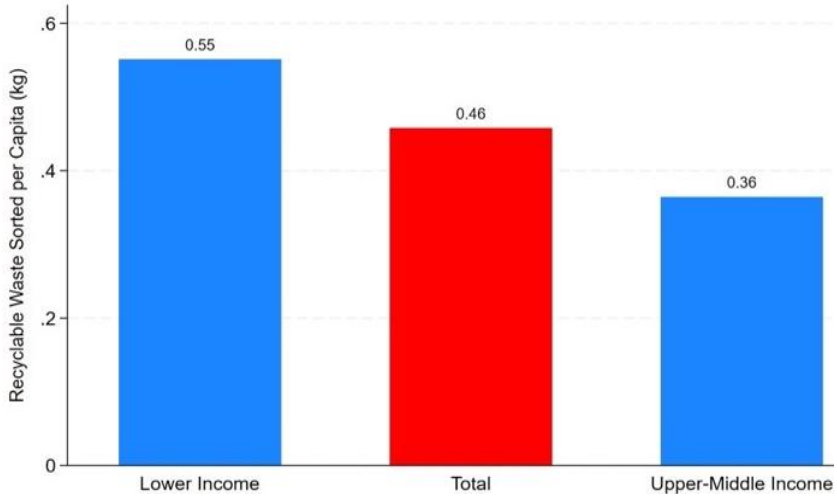


Figure 5. Average recyclable waste sorted (kg) per capita categorized by household income levels

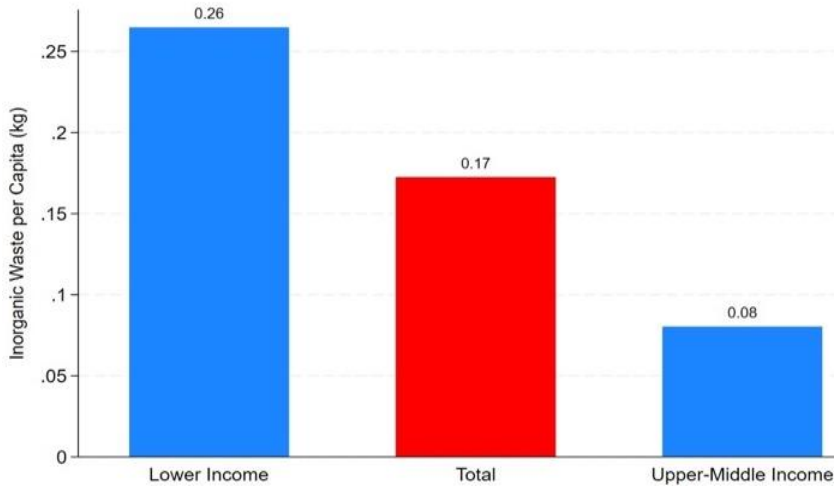


Figure 6. Daily inorganic waste (kg) per capita based on household income levels

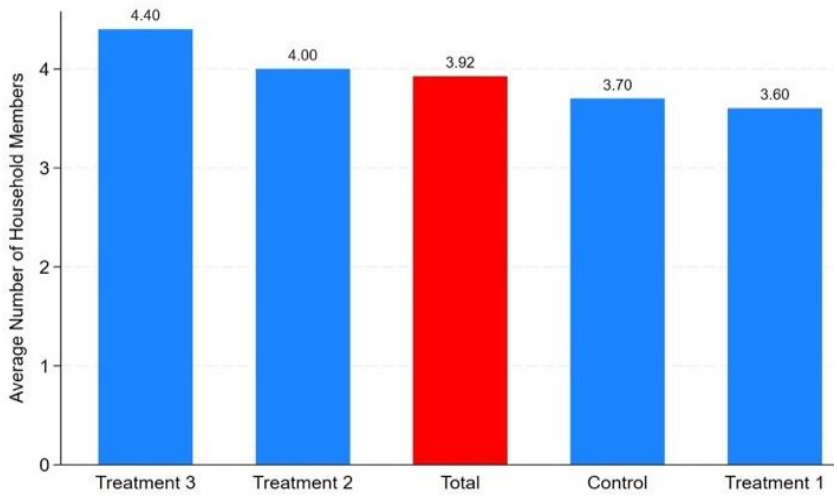


Figure 7. Average number of household members across different experimental groups

A strong difference in inorganic waste generation emerges across economic strata. Households in the lower-income group generated an average of 0.265 kg of inorganic waste per capita, substantially exceeding both the overall sample average (0.173

kg per capita) and the corresponding figure for upper-middle-income households (0.080 kg per capita) (Figure 6).

This pattern closely mirrors the distribution observed for sorted recyclable waste, suggesting that households in the lower economic stratum not only sorted more recyclables but also had a larger volume of inorganic materials available for sorting. Differences in recycling outcomes across socioeconomic groups are likely to reflect both variations in sorting behavior and the underlying amount of recyclable waste generated, underscoring the importance of accounting for baseline differences in waste generation when evaluating the effectiveness of waste-sorting interventions.

Household size appears to be relatively balanced across the experimental groups, suggesting that differences in waste-sorting outcomes are unlikely to be driven by substantial disparities in household composition. The average household consisted of approximately 3.93 members, with Treatment 3 recording the largest household size (4.4 members), followed by Treatment 2 (4.0 members), the control group (3.7 members), and Treatment 1 (3.6 members) as presented in Figure 7.

Although the variation is modest, household size remains an important factor to consider because larger households generally generate more waste as a consequence of higher consumption and a greater number of daily activities. As a result, households in Treatment 3 may have had more opportunities to generate both waste and recyclable materials than households in the other groups. Controlling for household size in subsequent analyses is therefore necessary to ensure that observed differences in waste generation and sorting performance reflect the effects of the interventions rather than variations in the number of household members.

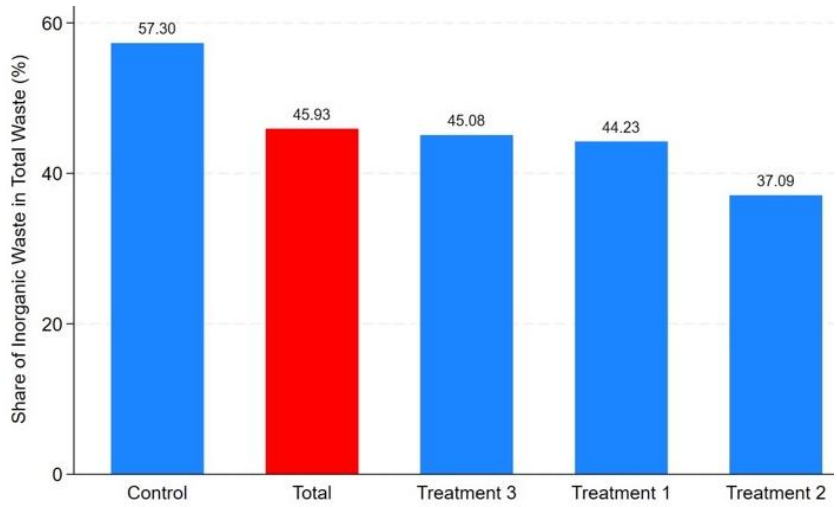


Figure 8. Share (%) of inorganic waste in total waste across treatment and control groups

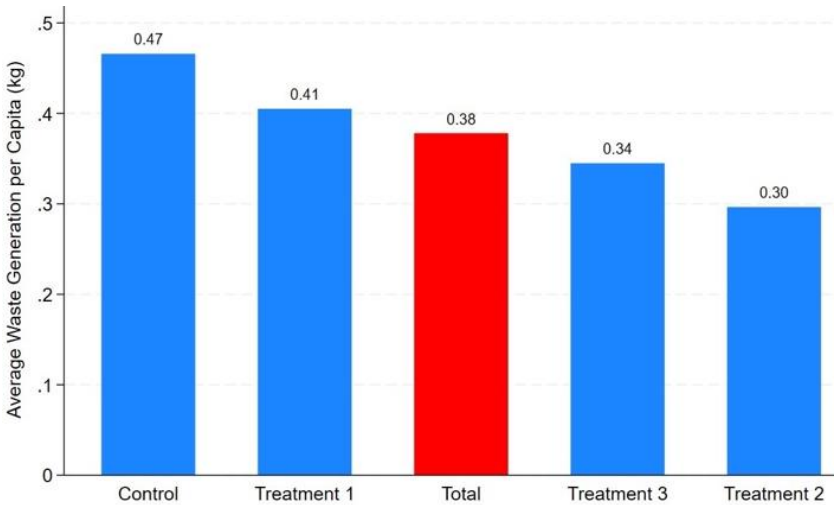


Figure 9. Average waste generation (kg) per capita by control and treatment groups

The composition of inorganic waste differed substantially across treatment groups, with the control group exhibiting the highest share of inorganic waste in total waste generation (57.30%), well above the sample average of 45.93%. In comparison, the proportion of inorganic waste was markedly lower among households receiving the interventions, ranging from 37.09% in Treatment 2 to approximately 45% in Treatments 1 and 3 (Figure 8).

This pattern is consistent with earlier findings showing that the control group also generated the largest volume of inorganic waste per capita, suggesting that households entered the experiment with different waste composition profiles. As a result, differences in recycling outcomes across groups cannot be interpreted solely as differences in sorting behavior but must also be viewed in relation to the amount of recyclable material available for sorting. The relatively low inorganic waste share observed in Treatment 2 further points to possible variations in consumption patterns and packaging use among

participating households.

Waste generation per capita also varied considerably across treatment groups, revealing important differences in baseline household waste profiles. The control group generated the largest amount of waste, averaging 0.47 kg per capita, compared with the overall sample average of 0.38 kg per capita (Figure 9).

In contrast, waste generation was lower across all treatment groups, ranging from 0.41 kg per capita in Treatment 1 to 0.30 kg per capita in Treatment 2, with Treatment 3 averaging 0.34 kg per capita. This pattern is consistent with previous findings showing that the control group also produced more inorganic waste and a higher proportion of inorganic materials in its waste stream.

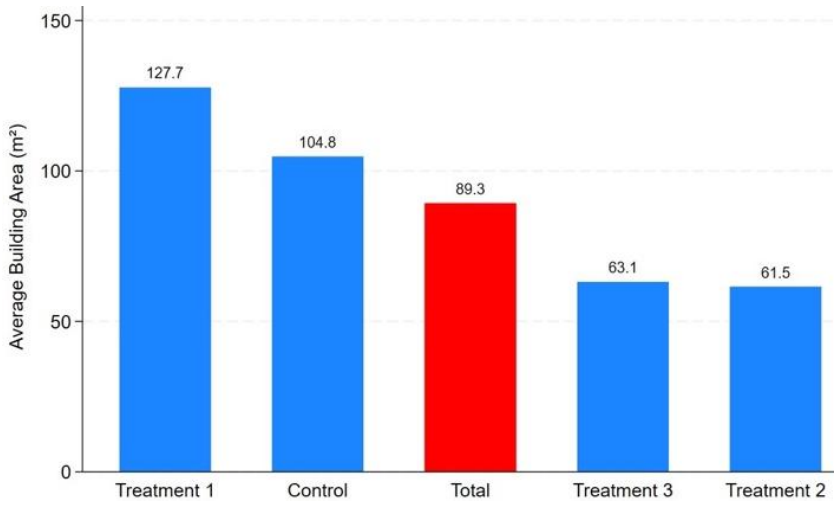


Figure 10. Comparison of average building area (m²) between control and treatment group

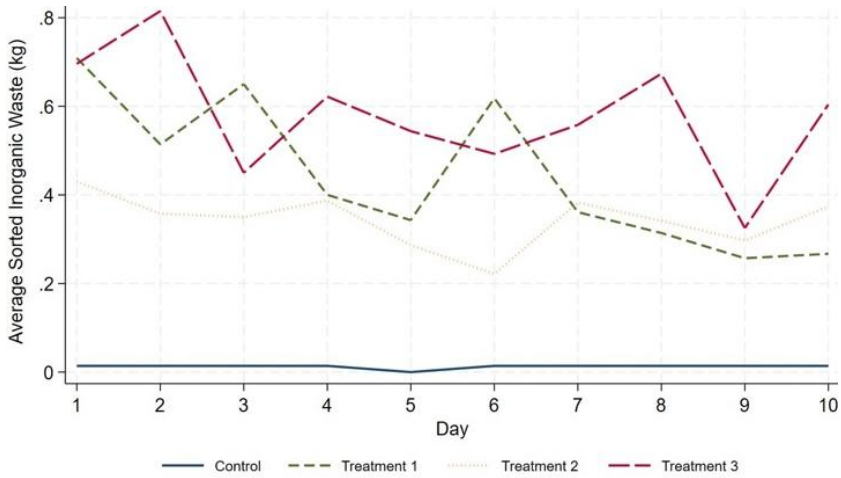


Figure 11. Daily average of sorted inorganic waste (kg) across treatment groups over a 10-day period

Housing characteristics varied noticeably across the experimental groups, particularly in terms of building size. Households in Treatment 1 occupied the largest dwellings, averaging 127.7 m², followed by the control group at 104.8 m², both above the overall sample average of 89.3 m². In contrast, households in Treatments 2 and 3 resided in considerably smaller homes, with average floor areas of 61.5 m² and 63.1 m², respectively (Figure 10).

These differences suggest that the groups were not fully comparable in their housing conditions and potentially in their socioeconomic profiles. Since larger dwellings may be associated with higher consumption levels and greater capacity to store and sort recyclable materials, housing characteristics could influence waste-generation and waste-sorting outcomes independently of the interventions. Therefore, building size is included as a control variable in the subsequent econometric analysis to ensure that estimated treatment effects are not confounded by pre-existing differences in household living conditions.

Across the ten-day observation period, households receiving the interventions consistently sorted substantially more inorganic waste than those in the control group, whose sorting activity remained close to zero throughout the study. Among the treatment groups, Treatment 3 demonstrated the strongest and most sustained performance, maintaining the highest average quantity of sorted inorganic waste on most observation days and reaching peaks of over 0.8 kg early in the intervention period (Figure 11).

Treatment 1 also generated relatively high sorting levels initially but exhibited a gradual decline toward the end of the observation period, suggesting that its effect may have weakened over time. In contrast, Treatment 2 produced lower but more stable sorting outcomes, with less strong day-to-day fluctuations. Taken together, these temporal patterns provide preliminary evidence that the interventions were associated with increased household waste-sorting activity, while also highlighting important differences in both the magnitude and persistence of behavioral responses across intervention types.

4.1.2 Determinants of household waste-sorting behavior

The effects of the treatment interventions on the amount of inorganic waste sorted for recycling is presented in Table 1.

Table 1 presents the pooled OLS estimates of the effects of the treatment interventions on the amount of inorganic waste sorted for recycling. Across all model specifications, the coefficients for Treatment 1, Treatment 2, and Treatment 3 are positive and statistically significant relative to the control group. In the baseline model, the estimated treatment effects are 0.431 kg, 0.330 kg, and 0.565 kg, respectively. After progressively controlling for household, housing, socioeconomic, and waste-service characteristics, the estimated effects remain highly significant and increase to 0.528 kg for Treatment 1, 0.403 kg for Treatment 2, and 0.612 kg for Treatment 3 in the full specification. These results indicate that the estimated treatment effects are robust to the inclusion of observable household characteristics. Across all specifications, Treatment 3 produces the largest increase in sorted inorganic waste, followed by Treatment 1 and Treatment 2.

Several control variables are also significantly associated with inorganic waste sorting. The number of domestic workers is negatively associated with the amount of sorted inorganic waste, whereas the number of bedrooms exhibits a positive relationship. In addition, households in the highest income category sort significantly more inorganic waste, while those in the upper-middle economic stratum sort less than households in the lower economic stratum. Overall, the treatment variables remain the strongest predictors of household waste-sorting behavior across all model specifications.

Table 1. Pooled ordinary least squares (pooled OLS) estimation

	Baseline	**+ HH Controls**	**+ Housing Types**	**+ Socio-Economic Controls**	**Full Model**
Treatment-1	0.431***	0.429***	0.499***	0.507***	0.528***
	(0.093)	(0.098)	(0.111)	(0.128)	(0.125)
Treatment-2	0.330***	0.315***	0.367***	0.396***	0.403***
	(0.054)	(0.059)	(0.052)	(0.076)	(0.077)
Treatment-3	0.565***	0.527***	0.604*	0.610***	0.612***
	(0.136)	(0.126)	(0.134)	(0.136)	(0.130)
Control	0	0	0	0	0
	(.)	(.)	(.)	(.)	(.)
Household size		0.035	0.027	0.041	0.055
		(0.030)	(0.029)	(0.037)	(0.041)
Number of maids		-0.049	-0.179**	-0.202***	-0.351
		(0.046)	(0.067)	(0.072)	(0.124)
Online shopping frequency		0.00052	-0.00525	-0.0147	-0.0351
		(0.0305)	(0.0291)	(0.0270)	(0.0315)
Building area (m^2)			-0.000568	-0.000737	-0.00140*
			(0.000443)	(0.000504)	(0.000759)
Number of bedrooms			0.158***	0.167***	0.172***
			(0.0580)	(0.0632)	(0.0573)
House rented			0	0	0
			(.)	(.)	(.)
House owned			-0.247*	-0.121	-0.0566
			(0.124)	(0.110)	(0.115)
Nonlanded house (reference)			0	0	0
			(.)	(.)	(.)
Landed house			0.0847	0.0683	0.0390
			(0.116)	(0.102)	(0.112)
Household head education: elementary (ref.)				0	0
				(.)	(.)
Household head education: Junior High				-0.291	-0.709*
				(0.251)	(0.407)
Household head education: Senior High				-0.0993	-0.0958
				(0.152)	(0.134)
Household head education: College				-0.231	-0.294
				(0.213)	(0.197)
Monthly income: <IDR 5.000.000 (ref)				0	0
				(.)	(.)
Monthly income: IDR 5.000.000- IDR 30.000.000				0.157	0.269
				(0.116)	(0.152)
Monthly income: >IDR 30.000.000				0.214*	0.584*
				(0.122)	(0.368)
Economic strata: low (ref.)				0	0
				(.)	(.)
Economic strata: middle-high				-0.146	-0.227*
				(0.113)	(0.119)
Waste collection fees					0.00000219
					(0.0000014)
Waste collection services: none (ref.)					0

					(.)
Waste collection services: yes					0.0581
					(0.131)
Separated bins: no (ref)					0
					(.)
Separated bins: yes					0.0477
					(0.0820)
Constant	0.0127	-0.104	-0.290*	-0.252**	-0.386**
	(0.0122)	(0.116)	(0.150)	(0.118)	(0.188)
Observations	400	400	400	400	400

Note: Household-clustered standard errors are reported in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

An important feature of the results is the stability of the treatment coefficients across all model specifications. The magnitude, sign, and statistical significance of the treatment effects remain largely unchanged as additional groups of control variables are introduced, including household, housing, socioeconomic, and waste-service characteristics. This pattern suggests that the positive association between the interventions and recyclable waste sorting is not highly sensitive to the inclusion of these observed factors. Moreover, the treatment coefficients remain substantially larger than those of most control variables throughout the estimation process, indicating that the interventions account for a meaningful share of the variation in household waste-sorting outcomes. The consistency of the estimated effects across progressively more comprehensive specifications provides additional confidence in the robustness of the main findings and motivates further examination using alternative panel-data estimators.

Table 2 presents the random effects estimates, which are highly consistent with the pooled OLS results. Before estimating the regression models, the Breusch-Pagan Lagrange Multiplier test was conducted to determine whether a panel estimator was preferable to pooled OLS. The null hypothesis of no household-level random-effect variance was rejected ($chibar^2(1) = 100.29$, $p < 0.001$), indicating significant variation across households and supporting the use of the random-effects estimator. All treatment variables remain positive and statistically significant at the 1% level across specifications. In the fully adjusted model, the estimated effects are 0.520 kg for Treatment 1, 0.396 kg for Treatment 2, and 0.590 kg for Treatment 3, with Treatment 3 consistently exhibiting the largest effect. The estimated relationships for the control variables also remain largely unchanged, including the negative association for the number of domestic workers, the positive association for the number of bedrooms, and higher waste sorting among high-income households. The close agreement between the two estimators indicates that the main findings are robust to alternative panel-data specifications.

Table 2. Random effects estimation

	Baseline	**+ HH Controls**	**+ Housing Types**	**+ Socio-economic Controls**	**Full Model**
Treatment-1	0.431***	0.430***	0.490***	0.495***	0.520***
	(0.093)	(0.097)	(0.109)	(0.123)	(0.124)
Treatment-2	0.330***	0.313***	0.356***	0.388***	0.396***
	(0.055)	(0.059)	(0.052)	(0.072)	(0.079)
Treatment-3	0.565***	0.528***	0.595*	0.600***	0.590***
	(0.136)	(0.126)	(0.131)	(0.132)	(0.114)
Control	0	0	0	0	0
	(.)	(.)	(.)	(.)	(.)
Household size		0.035	0.029	0.042	0.060
		(0.030)	(0.029)	(0.037)	(0.047)
Number of maids		-0.050	-0.161***	-0.182***	-0.378**
		(0.046)	(0.061)	(0.069)	(0.178)
Online shopping frequency		0,003	-0.002	-0.011	-0.034
		(0.030)	(0.029)	(0.027)	(0.036)
Building area (m^2)			-0.000	-0.001	-0.001
			(0.000)	(0.000)	(0.001)
Number of bedrooms			0.135***	0.139**	0.141***
			(0.047)	(0.056)	(0.050)
House rented			0	0	0
			(.)	(.)	(.)
House owned			-0.223*	-0.093	-0.021
			(0.118)	(0.109)	(0.128)
Nonlanded house (reference)			0	0	0
			(.)	(.)	(.)
Landed house			0.067	0.059	0.054
			(0.082)	(0.067)	(0.074)
Household head education: Elementary (ref.)				0	0
				(.)	(.)
Household head education: Junior High				-0.273	-0.772
				(0.246)	(0.592)
Household head education: Senior High				-0.104	-0.111
				(0.148)	(0.157)

Household head education: College				-0.234	-0.317
				(0.208)	(0.242)
Monthly income: <IDR 5.000.000 (ref)				0	0
				(.)	(.)
Monthly income: IDR 5.000.000- IDR 30.000.000				0.161	0.292
				(0.114)	(0.195)
Monthly income: >IDR 30.000.000				0.218*	0.654*
				(0.122)	(0.368)
Economic strata: low (ref.)				0	0
				(.)	(.)
Economic strata: middle-high				-0.142	-0.227*
				(0.112)	(0.121)
Waste collection fees					0.000
					(0.000)
Waste collection services: none (ref.)					0
					(.)
Waste collection services: yes					0.027
					(0.120)
Separated bins: no (ref)					0
					(.)
Separated bins: yes					0.048
					(0.088)
Constant	0.013	-0.110	-0.261*	-0.222**	-0.362*
	(0.012)	(0.116)	(0.137)	(0.091)	(0.198)
Observations	400	400	400	400	400

Note: Household-clustered standard errors are reported in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Beyond the statistical significance of the treatment variables, the random effects estimates reveal a high degree of stability across alternative model specifications. The treatment coefficients remain positive and change only modestly as successive blocks of household, housing, socioeconomic, and waste-service controls are introduced, suggesting that the estimated relationships are not highly sensitive to model specification. Likewise, the signs and significance of the main control variables remain largely consistent throughout the estimation process. This stability, together with the close correspondence between the random effects and pooled OLS estimates, indicates that the principal empirical patterns observed in the data are preserved across estimation approaches, thereby providing a consistent basis for the subsequent discussion of the intervention effects.

4.1.3 Behavioral continuity after withdrawal

On the withdrawal day, the mean amount of inorganic waste sorted remained stable or increased across the treatment groups (Table 3). Treatment 1 recorded a small increase from 0.257 kg on Day 9 to 0.267 kg on Day 10, while Treatment 2 increased from 0.297 kg to 0.374 kg. Neither change was statistically significant. Treatment 3 exhibited a larger increase from 0.325 kg to 0.604 kg, corresponding to a within-household increase of 0.279 kg that was statistically significant at the 5% level. In comparison, the control group remained unchanged at 0.014 kg.

Table 3. Waste-sorting outcomes on Day 9 and 10

Experimental Group	Day 9 Mean	Day 10 Mean	Change from Day 9 to Day 10	Paired-Test *p*-Value	Adjusted Day 10 Difference from Control
Control	0.014	0.014	0.000	—	Reference
Treatment 1	0.257	0.267	0.010	0.928	0.083 (0.188)
Treatment 2	0.297	0.374	0.077	0.572	0.258 (0.181)
Treatment 3	0.325	0.604	0.279**	0.023	0.424*** (0.151)

Remarks: The outcome is the amount of inorganic waste sorted for recycling, measured in kilograms. Day 9 represents the final intervention day, while Day 10 represents the withdrawal day. The fourth and fifth columns report within-household changes and paired t-test results. The final column reports baseline-adjusted differences relative to the control group, estimated by controlling for the Day 1 amount of sorted inorganic waste and socioeconomic stratum. The robust standard errors are reported in parentheses. The treatment indicators are jointly significant, $F(3, 34) = 3.33$, $p = 0.031$. **$p < 0.05$; ***$p < 0.01$.

A baseline-adjusted regression was subsequently estimated to compare Day 10 outcomes across the experimental groups while controlling for the amount of inorganic waste sorted on Day 1 and socioeconomic stratum. Treatment 3 sorted approximately 0.424 kg more inorganic waste than the control group on Day 10, and this difference was statistically significant at the 1% level. The adjusted differences for Treatments 1 and 2 were positive but not statistically significant. These findings indicate that sorting behavior did not immediately deteriorate following treatment withdrawal and provide evidence consistent with immediate behavioral persistence, particularly under Treatment 3. Nevertheless, because behavior was observed for only one withdrawal day, the results cannot establish longer-term behavioral persistence.

4.2 Discussion

4.2.1 Household responses to alternative waste management interventions

The transition toward a circular economy requires more than the provision of waste management infrastructure; it depends fundamentally on households' willingness to participate in waste separation at the source [35, 36]. Although

source separation is widely recognized as the foundation of effective recycling systems, participation rates remain highly heterogeneous because households respond differently to educational messages, physical facilities, and economic incentives [35]. Consequently, understanding which intervention is capable of producing the strongest behavioral response becomes a critical issue for designing effective municipal waste management policies. Circular economy policies therefore cannot be evaluated solely from the downstream efficiency of recycling systems but must also consider how different interventions influence household decision-making at the point where waste is generated [36].

The descriptive statistics reveal a pattern that is considerably more complex than a simple comparison of treatment outcomes. Although all intervention groups successfully generated recyclable waste that was subsequently separated, none produced a larger absolute quantity of sorted recyclable waste than the control group. Households assigned to the control group generated an average of 0.573 kg of recyclable waste per capita, substantially exceeding the sample average of 0.459 kg per capita, whereas the intervention groups produced between 0.371 kg and 0.451 kg per capita. Among the intervention strategies, Treatment 3 consistently achieved the highest recycling performance, followed by Treatment 1, while Treatment 2 recorded the lowest volume of sorted recyclable waste.

This distinction is particularly important within the broader circular economy framework. Previous studies have emphasized that successful circular economy implementation depends not only on recycling technologies but also on behavioral participation throughout the consumption cycle [36, 37]. Household waste generation, consumption patterns, and recycling behavior are therefore jointly determined rather than operating independently. Evaluating recycling program solely from the quantity of recyclable materials collected risks conflating behavioral change with underlying differences in household consumption. This finding reinforces recent arguments that household-level circular economy policies should employ proportional or behavioral indicators alongside absolute waste quantities when assessing program effectiveness [35].

Despite these baseline differences, a clear hierarchy emerges among the intervention strategies. Treatment 3 consistently outperformed the other treatment groups, while Treatment 2 remained the least effective throughout the descriptive analysis. This pattern is theoretically meaningful because the three interventions represent distinct behavioral mechanisms. Treatment 1 primarily reduced physical barriers by providing waste-sorting facilities, Treatment 2 attempted to influence behavior through environmental education, whereas Treatment 3 combined infrastructural support with direct monetary incentives for recyclable waste. Rather than merely increasing environmental awareness, Treatment 3 altered the household decision environment by attaching an immediate economic value to waste separation.

From a behavioral economics perspective, this finding is unsurprising. Waste sorting constitutes a repetitive domestic routine performed under limited time, attention, and cognitive resources. In such settings, individuals frequently rely on habitual decision-making instead of deliberate environmental reasoning. Immediate and tangible incentives therefore reduce the perceived opportunity costs associated with waste separation and provide continuous reinforcement for behavioral repetition [37, 38]. Financial rewards transform recyclable waste from an environmental responsibility into an economic resource, thereby increasing the likelihood that households consistently engage in sorting activities [38, 39]. This mechanism helps explain why the incentive-based intervention produced stronger behavioral responses than interventions relying exclusively on information or infrastructure.

The relatively weak performance of Treatment 2 deserves particular attention because it appears inconsistent with the conventional assumption that environmental education naturally leads to environmentally responsible behavior. Rather than contradicting previous research, the present findings suggest that education alone may be insufficient to modify deeply embedded household routines during the initial stages of program implementation. Educational interventions primarily reshape knowledge, awareness, and environmental attitudes. However, translating these cognitive changes into repeated daily practices requires habit formation, behavioral reinforcement, and supportive domestic conditions. Consequently, improvements in environmental understanding do not necessarily produce immediate changes in observable recycling behavior, particularly when households continue to face practical constraints or receive no direct incentives to modify existing routines. This interpretation is consistent with the growing body of literature arguing that information-based interventions become substantially more effective when complemented by practical facilitation and behavioral reinforcement mechanisms [39-41].

Interestingly, these findings also provide an alternative interpretation of the relationship between environmental awareness and recycling behavior. Much of the existing literature implicitly assumes that knowledge precedes behavior [23, 40]. The present evidence instead suggests that behavior itself may become an important pathway through which environmental awareness gradually develops. When households repeatedly separate recyclable waste because doing so is convenient or economically rewarding, the repeated practice may eventually become internalized as a social norm and an everyday habit [37, 38, 42]. In other words, behavioral engagement may precede attitudinal change rather than simply resulting from it. This perspective shifts the focus of household waste management policy from attempting to persuade individuals through information alone toward designing institutional environments that make pro-environmental behavior easier, more rewarding, and eventually self-sustaining.

The findings therefore contribute to the growing discussion within circular economy research by demonstrating that successful household recycling program requires an integrated policy architecture rather than isolated interventions. Infrastructure reduces operational barriers, education builds environmental understanding, while economic incentives accelerate behavioral adoption during the early phases of policy implementation. None of these instruments should be viewed as substitutes for one another. Instead, they operate through different behavioral pathways that collectively determine household participation in waste separation. Accordingly, municipal waste management policies should move beyond awareness campaigns as the primary policy instrument and instead combine educational program with practical facilities and carefully designed incentive schemes capable of transforming waste sorting into a routine component of everyday household life [35, 37-42].

4.2.2 Multivariate evidence on the effectiveness of waste-sorting interventions

The multivariate estimates substantially alter the interpretation suggested by the initial descriptive comparison. While the raw group averages appeared to show that the control group produced a larger absolute amount of recyclable waste, the regression models indicate that households receiving any of the three interventions sorted significantly more inorganic waste than untreated households after observable household and service characteristics were taken into account. In the baseline pooled OLS model, Treatments 1, 2, and 3 were associated with increases of approximately 0.431 kg, 0.330 kg, and 0.565 kg, respectively, relative to the control group. More importantly, all three coefficients remained positive and statistically significant at the 1% level as household composition, housing conditions, socioeconomic characteristics, and waste-management services were introduced successively into the models. In the fully adjusted specification, the corresponding effects increased to 0.528 kg for Treatment 1, 0.403 kg for Treatment 2, and 0.612 kg for Treatment 3.

The treatment coefficients also increased rather than declined after additional controls were introduced. For Treatment 1, the estimated coefficient rose from 0.431 in the baseline model to 0.528 in the full model. Treatment 2 increased from 0.330 to 0.403, while Treatment 3 increased from 0.565 to 0.612. This pattern suggests that some observed household characteristics were negatively associated with treatment assignment or sorting performance and had partially suppressed the treatment effects in the simpler models. Put differently, the treated households did not necessarily possess more favorable baseline characteristics. The interventions generated positive sorting outcomes despite differences in economic strata, housing size, domestic labor arrangements, and access to waste services.

4.2.3 Why the integrated incentive package produced the strongest response

Treatment 3 consistently produced the largest estimated impact across every model. In the full pooled OLS specification, its coefficient of 0.612 was approximately 16% larger than that of Treatment 1 and more than 50% larger than that of Treatment 2. The random effects model yielded a nearly identical hierarchy, with estimated effects of 0.590, 0.520, and 0.396 kg for Treatments 3, 1, and 2, respectively. This consistency indicates that the stronger performance of Treatment 3 cannot easily be attributed to a single model specification.

The finding supports the argument that the purchase of sorted recyclable waste altered the perceived value of household waste. Under ordinary disposal arrangements, separating waste requires time, storage space, attention, and additional domestic effort, while the benefits are largely collective, delayed, and environmentally diffuse. The incentive mechanism converts at least part of that collective benefit into a private and observable return. It therefore reduces the perceived net cost of participation and gives households a concrete reason to repeat the activity [37, 38].

Experimental and field-based evidence similarly shows that monetary and non-monetary incentives can increase recycling participation by raising the perceived value of recyclable materials [37, 38]. Wang et al. [37] found that economic incentives positively affected recycling intentions through perceived value, while Yang et al. [38] reported a substantial increase in the amount of recyclables collected under an incentive-based household recycling program. The present findings advance this literature by using actual quantities of sorted household waste rather than relying solely on stated intentions or self-reported participation.

The effect should nevertheless be interpreted as behavioral activation, rather than proof that monetary payment will permanently sustain sorting behavior. Financial incentives may be effective because they prompt participation during the program period, but their long-term influence depends on whether repeated action becomes habitual, socially supported, and institutionally embedded. Ling et al. [42] caution that the effectiveness of incentive programs varies with neighborhood networks, community norms, and the interpersonal context through which the program is promoted. Thus, Treatment 3 appears highly effective within the present intervention window, but increasing the payment indefinitely would not necessarily generate proportionate increases in sorting. At some point, the marginal behavioral response may diminish, program costs may rise, or intrinsic environmental motivation may be displaced by an expectation of payment.

This point is especially relevant for policy design. The treatment should not be framed as paying residents indefinitely for an activity that ought eventually to become routine. A more sustainable design would use incentives as a transitional mechanism: rewards initiate participation, reliable collection systems reduce inconvenience, education explains the social and environmental purpose, and repeated performance gradually normalizes sorting as an everyday practice. The strongest policy package is therefore unlikely to be an incentive operating in isolation. It is more plausibly a sequenced combination in which the incentive attracts attention and participation, infrastructure makes sorting feasible, and education supports internalization.

4.2.4 The facility treatment and the importance of reducing practical barriers

Treatment 1 generated the second-largest effect. In the fully controlled pooled OLS model, households receiving the facility-based intervention sorted approximately 0.528 kg more inorganic waste than the control group, while the corresponding random effects coefficient was 0.520 kg. The small difference between these two estimates indicates that the result is not sensitive to whether unobserved household heterogeneity is represented through a random effects structure.

The effectiveness of Treatment 1 suggests that a meaningful portion of inadequate waste separation is not caused by opposition to recycling or a complete absence of environmental concern. Instead, households may fail to sort because the domestic environment does not make separation convenient. Providing separate bins changes the physical architecture of household decision-making. It reduces the effort required to remember categories, locate temporary storage, and keep organic and inorganic waste apart. In behavioral terms, the intervention decreases friction at the moment the decision is made.

This interpretation is consistent with the broader waste-separation literature, which identifies convenience and facilitating conditions as core determinants of actual behavior [23, 43]. A systematic review of 279 studies by Zhang found that convenience, knowledge, intention, and norms were among the most consistently supported micro-level determinants of waste separation [23]. Wang et al. [43]

likewise show that facilitating conditions and habit influence both intention and realized municipal waste-separation behavior. These studies help explain why the provision of basic facilities can generate a substantial treatment effect even without direct payment.

The result also carries an operational warning. The effect of physical facilities depends on their continued usability. A separate bin that is damaged, too small, inconveniently located, or followed by mixed collection may quickly lose credibility. Households are unlikely to sustain separation when they observe that separately stored materials are recombined downstream. The facility treatment therefore requires more than the one-off distribution of containers. It must be supported by maintenance, predictable collection schedules, clear labelling, and visible preservation of separation through the subsequent waste chain.

4.2.5 Why education generated the smallest, yet still significant, effect

Treatment 2 consistently produced the smallest coefficient, but its effect remained positive and strongly significant. This distinction matters. The results do not show that education failed. They show that, during the observation period, education produced a smaller measurable increase in sorted waste than direct facilities or the combination involving a purchasing incentive.

In the full pooled OLS model, Treatment 2 increased sorted inorganic waste by approximately 0.403 kg, compared with 0.528 kg for Treatment 1 and 0.612 kg for Treatment 3. The random effects estimate was similarly positive at 0.396 kg. Therefore, describing education as "ineffective" would be statistically incorrect. The more defensible conclusion is that education alone was less behaviorally intensive in the short term.

This result can be understood through the gap between cognitive learning and routine action. Educational interventions may strengthen knowledge, awareness, and perceived responsibility, but household waste sorting requires repeated action in a domestic setting. Information does not automatically eliminate time constraints, limited storage, uncertainty over waste categories, or the inconvenience of separate disposal. Matiiuk and Liobikienė [40] found that although respondents frequently regarded informational tools as important, the existing level of information did not necessarily translate into stronger waste-sorting behavior. Ma et al. [39] similarly note that the effects of information interventions are mixed and depend on the method used, technical convenience, and the opportunity and time costs borne by households.

The present findings are therefore consistent with the proposition that environmental education is more effective when it is experiential and tightly connected to the activity being promoted. General messages concerning pollution, sustainability, or the circular economy may improve attitudes without resolving the immediate question faced by households: what item belongs in which container, when it should be separated, where it will be stored, and who will collect it. Education should consequently be redesigned as a practical intervention rather than treated as the passive transfer of environmental knowledge.

For example, education could include household demonstrations, category-specific sorting guides, feedback on contamination, visual labels attached directly to the bins, and repeated reminders linked to collection days. Such measures move education from an abstract awareness program toward an action-oriented learning process. The systematic review by Trushna et al. [41], covering 82 household waste-segregation interventions, found considerable heterogeneity in both intervention design and effectiveness and highlighted the need to compare individual intervention components more carefully. The current study responds directly to that need by showing that information, infrastructure, and incentives are not behaviorally equivalent.

4.2.6 Stability of the results across pooled ordinary least squares and random effects

The similarity between the pooled OLS and random effects estimates is a notable feature of the analysis. Under Pooled OLS, the full-model treatment coefficients were 0.528, 0.403, and 0.612. Under random effects, the corresponding values were 0.520, 0.396, and 0.590. The signs, magnitude ranking, and statistical significance were therefore preserved across estimation approaches.

This consistency strengthens confidence that the substantive findings do not arise from a particular estimator. Treatment 3 remains the most effective, Treatment 1 occupies an intermediate position, and Treatment 2 produces the smallest but still meaningful effect. The similarity also suggests that time-invariant differences between households did not materially overturn the average treatment relationships.

The daily graph reinforces the multivariate results by showing that the treatment groups sorted substantially more inorganic waste than the control group throughout most of the observation period. Treatment 3 displayed the highest and most persistent sorting levels; Treatment 1 performed strongly during the earlier days before gradually weakening; and Treatment 2 maintained a lower but relatively stable response. The regression estimates therefore summarize a dynamic pattern rather than a single end-of-program difference. Treatment 3 appears to combine magnitude and persistence, while Treatment 1 may have experienced novelty decay and Treatment 2 may have produced a slower but steadier response.

4.2.7 Household size and the availability of recyclable materials

The number of household members was positive in all controlled specifications but was not statistically significant. In the full pooled OLS model, the coefficient was 0.0552, while the random effects estimate was 0.060. The direction is intuitively plausible: households with more members may consume more goods and consequently generate a larger quantity of potentially recyclable material. Nevertheless, the absence of statistical significance indicates that household size did not independently explain the quantity sorted once the treatment and other household characteristics were included.

One explanation is that the dependent variable reflects sorting performance rather than waste generation alone. A larger household may generate more waste, but it also faces greater coordination difficulties. Different members may possess different levels of awareness, follow different routines, or use waste containers inconsistently. Accordingly, the positive quantity effect of additional household members may be offset by a negative coordination effect.

The finding also highlights the value of per-capita and ratio-based robustness measures. If the dependent variable is expressed in absolute kilograms, larger households have greater physical opportunities to generate and sort waste. Re-

estimating the models with sorted inorganic waste per capita, or the proportion of inorganic waste successfully separated, would help establish whether the treatments improved behavioral efficiency rather than merely increasing the quantity collected.

4.2.8 The negative association with domestic workers

The number of domestic workers was one of the most consistent household-level predictors. Its coefficient became increasingly negative as additional controls were introduced. Under pooled OLS, the estimate declined from −0.0486 in the household-control model to −0.361 in the full model, significant at the 1% level. Under random effects, the corresponding full-model estimate was −0.378, significant at the 5% level.

This is an intriguing result because domestic workers might initially be expected to improve household waste management by increasing the labor available for domestic tasks. The negative coefficient suggests that delegation may instead weaken the consistency of waste-sorting practices. The person receiving environmental information, agreeing to participate in the intervention, or making household consumption decisions may not be the same person who physically handles the waste. This division of responsibility can create an implementation gap.

The effect may also reflect uneven training. Environmental programs often target household heads or registered participants, whereas domestic workers may receive only indirect instructions. If the activity is perceived as an additional obligation without personal reward, understanding, or monitoring, sorting quality may decline. This interpretation is compatible with a practice-based perspective: waste sorting is not simply an individual attitude but a coordinated household routine involving materials, competence, and shared responsibility.

From a policy standpoint, interventions should engage the person who actually performs waste-related tasks. Program registration should identify primary waste handlers, and educational demonstrations should include household employees, caregivers, and other members who manage the daily waste stream. This finding is potentially novel because much of the literature treats the household as a single decision-making unit, whereas the present evidence indicates that internal delegation shapes environmental performance.

Still, the coefficient should be interpreted cautiously. The number of domestic workers may proxy for unobserved household characteristics such as lifestyle, consumption intensity, work patterns, or the degree to which domestic tasks are delegated. A larger sample and more detailed measures of who sorts the waste would be needed before concluding that domestic-worker employment itself reduces sorting.

4.2.9 Online-shopping frequency

Online-shopping frequency was negative in the more complete specifications, but the coefficient was statistically insignificant. In the full models, it was approximately −0.035 under pooled OLS and −0.034 under random effects. A negative relationship may appear surprising because online purchasing often increases packaging materials. However, higher packaging generation does not necessarily translate into a higher quantity sorted. Some packaging may be mixed with residual waste, reused, stored temporarily, or disposed of outside the study's measurement process.

The non-significant result suggests that purchase frequency alone is too crude to capture the waste implications of e-commerce. The type of product, packaging material, parcel size, reuse practices, and frequency of consolidated delivery may be more relevant than the number of transactions. Future analysis could distinguish cardboard, plastic wrapping, bubble packaging, and reusable containers. The result also indicates that treatment effects were not simply driven by households receiving more online-shopping packages.

4.2.10 Housing size, storage capacity, and the number of bedrooms

Building and land area displayed a small negative coefficient, reaching marginal significance only in the full pooled OLS model. In contrast, the number of bedrooms was consistently positive and significant. The full pooled OLS estimate for bedrooms was 0.172, significant at the 1% level, while the full random effects estimate was 0.141, also significant at the 1% level.

The opposing patterns suggest that the number of bedrooms may capture household organization more effectively than total property area. A large land or building area does not automatically provide a convenient place for recyclable storage, particularly where outdoor areas, shared spaces, or non-residential sections account for a substantial share of the property. Bedrooms, by contrast, may reflect the functional size of the dwelling, the number of occupants, or the number of distinct activity zones in the household.

The positive bedroom coefficient may also indicate that households with greater internal space can store separated recyclables until collection or purchase. Storage is a frequently overlooked constraint in source-separation systems. Households may be willing to sort but unable to retain bulky plastics, bottles, cardboard, or metal containers when collection is infrequent. Thus, the result supports the view that waste-sorting behavior depends partly on material capacity, not only environmental intention.

Nevertheless, multicollinearity should be examined because building area, number of bedrooms, household size, income, and economic stratum are conceptually related. Variance inflation factors or a correlation matrix should be reported. If these measures are strongly correlated, the individual coefficients may be unstable even though the treatment estimates remain robust.

4.2.11 Home ownership and housing type

Home ownership was negative and marginally significant when first introduced, but lost statistical significance after socioeconomic and service controls were added. Housing type was also insignificant throughout. These results indicate that formal tenure and dwelling type did not independently determine sorting performance once other conditions were considered.

The disappearance of the ownership effect suggests that its initial association may have reflected socioeconomic composition rather than ownership itself. Owners and renters may differ in income, household structure, location, or access to collection services, but tenure does not necessarily affect the day-to-day mechanics of sorting. This is substantively useful: the intervention appears applicable across housing-tenure categories rather than being effective only among homeowners.

At the same time, broad housing categories may hide relevant variation. Detached houses, apartments, gated communities, informal settlements, and mixed-use dwellings

can differ substantially in collection access, storage space, and collective-management arrangements. Future research should employ more granular indicators of housing density and communal waste infrastructure.

4.2.12 Education level and the knowledge-behavior gap

None of the higher educational categories exhibited a positive significant relationship with sorted waste. In the pooled OLS full model, the coefficients for junior secondary, senior secondary, and tertiary education were negative, with junior secondary reaching only marginal significance. The random effects results followed the same general pattern but were statistically insignificant.

This result is important because it challenges the assumption that formal education automatically produces superior environmental practice. Formal schooling may improve general knowledge and analytical capacity, but waste separation is a highly specific behavioral routine. Unless environmental knowledge is translated into clear sorting competence, appropriate facilities, and repeated domestic action, educational attainment may have little observable effect.

The result also reinforces the weaker relative performance of Treatment 2. Both findings point toward a knowledge–behavior gap: education can create awareness, but awareness is neither a sufficient condition nor a direct proxy for actual sorting. Recent reviews identify knowledge as an important determinant, but they also show that its effect operates alongside convenience, intentions, norms, policy settings, and economic conditions rather than independently [23, 41].

The negative signs should not be interpreted as evidence that more educated households are less environmentally responsible. The educational categories may be correlated with income, occupation, time constraints, housing location, or the use of external domestic labor. Small subgroup sizes may also produce imprecise estimates. The appropriate conclusion is that formal education did not provide additional explanatory power in this sample after the intervention and other household characteristics were controlled.

4.2.13 Income and economic-stratum results

Income produced a more complex pattern. Relative to households earning below Rp5 million, households in the highest income category sorted more inorganic waste. In the fully adjusted pooled OLS model, the coefficient for income above Rp30 million was 0.584, significant at the 5% level. The random effects coefficient was 0.654, although only marginally significant. The middle-income category was also positive, but its significance was weaker and less stable.

At the same time, the broader upper-middle economic-stratum indicator was negative. In both full models, upper-middle households sorted approximately 0.227 kg less than lower-stratum households, significant at the 10% level. At first sight, the positive income coefficient and negative economic-stratum coefficient seem contradictory. They should instead be interpreted as evidence that income and social-economic classification capture different dimensions.

Current household income may increase consumption and the availability of recyclable materials, thereby raising the absolute quantity that can be sorted. Economic stratum may additionally capture lifestyle, occupational structure, housing context, the outsourcing of domestic work, and the subjective value attached to small recycling payments. Lower-stratum households may be more accustomed to retaining materials with resale value or interacting with informal collectors and waste banks. Upper-middle households may have less motivation to perform sorting when the monetary return is considered small relative to their opportunity cost of time.

The descriptive findings support this interpretation: lower-stratum households recorded a larger average amount of sorted waste than upper-middle households, but they also generated substantially more inorganic waste. Therefore, part of the lower-stratum advantage reflects material availability, while part may reflect stronger sensitivity to the recovery value of recyclables.

The simultaneous inclusion of income categories and economic stratum deserves additional diagnostic attention. If the strata were themselves constructed partly from income, including both in the same regression may generate multicollinearity or make the coefficients difficult to interpret. The manuscript should explain clearly how economic stratum was defined and provide robustness models that include either income or stratum separately. Doing so would establish whether the negative upper-middle effect survives alternative socioeconomic specifications.

4.2.14 Waste fees, collection services, and separate containers

Waste-collection fees, the availability of collection services, and the prior presence of separate containers were statistically insignificant in the fully controlled models. This does not necessarily mean that waste-management services are unimportant. Instead, the measures may not capture service quality or actual household experience in sufficient detail. For example, a binary indicator for collection availability does not distinguish daily from weekly collection, reliable from irregular service, separated from mixed transport, or formal collection from informal pickup. Similarly, the presence of separate bins does not show whether the bins are appropriately sized, clearly labelled, conveniently located, regularly used, or supported by downstream separation.

The insignificance of the pre-existing-container variable also strengthens the interpretation of Treatment 1. Simply possessing separate containers is not equivalent to receiving a structured facility intervention. Program implementation may draw attention to the bins, clarify their purpose, create expectations of participation, and connect their use to monitoring or collection. The treatment effect therefore reflects an organized behavioral package rather than the physical object alone.

Waste fees may also be too homogeneous or weakly linked to the quantity of waste produced to influence behavior. A flat monthly fee does not create the marginal price signal found in pay-as-you-throw systems. Consequently, households face little direct financial benefit from reducing or separating waste merely because they pay a routine collection charge.

4.2.15 Model constants and substantive interpretation

The constant became negative and significant in the more complete models. In the full pooled OLS specification, it was approximately −0.386, while the random effects estimate was −0.362. The intercept has limited substantive meaning because it represents the predicted quantity for a reference household with zero values for all continuous variables and belonging to every omitted category. Such a household may not be realistic. The negative constant therefore should not be interpreted as implying negative waste sorting.

To make the results more intuitive, the paper could report adjusted predictions or marginal means for each treatment

group. These would show the expected sorted quantity for a household with observed or average characteristics and would communicate the treatment differences more clearly than the raw intercept.

4.2.16 Integrated interpretation of the regression evidence

Taken as a whole, the regression results reveal three central patterns. First, all interventions worked. The provision of facilities, education combined with facilities, and the incentive-based package each produced significantly more sorted inorganic waste than no intervention. Thus, the study does not support a simple dichotomy between successful and unsuccessful treatments.

Second, the mechanisms were not equally powerful within the short observation period. Treatment 3 generated the largest and most persistent response, suggesting that attaching economic value to recyclable waste produced the strongest immediate behavioral reinforcement. Treatment 1 ranked second, showing that reducing practical friction can generate substantial action even without payment. Treatment 2 remained positive but smaller, indicating that education may require more time, repetition, and practical integration before cognitive change becomes fully visible in measured waste quantities.

Third, household waste sorting is socially and materially organized. Domestic labor arrangements, functional housing space, income, and economic stratum mattered more than formal education, tenure status, or the mere existence of collection services. The household should therefore not be conceptualized as a uniform individual decision-maker. Sorting is undertaken through routines shared, or delegated, among household members, within physical space, under competing demands on time and attention.

The results consequently support a layered model of household waste intervention. Infrastructure establishes the material possibility of sorting; education develops competence and meaning; incentives create immediate motivation; and repetition supports habit formation. Policies relying on only one layer will leave other constraints unresolved. Information without facilities raises awareness but leaves practical barriers intact. Facilities without continued collection and reinforcement may experience declining use. Incentives without education or institutional continuity may create temporary compliance without durable environmental commitment.

The contribution of this study lies in demonstrating these differences using observed household waste quantities. Much of the literature focuses on intention, willingness, or self-reported practices [37, 38, 43]. In contrast, the present evidence shows how alternative policy instruments translate into measurable material recovery over time. This provides a more direct foundation for circular-economy policy because it links household behaviour to the actual flow of recoverable resources [36].

5. CONCLUSIONS

5.1 Summary

This study examined how household waste-sorting behavior responds to three increasingly intensive interventions. The interventions included the provision of sorting facilities, the addition of practical information and scheduled collection, and the addition of monetary incentives for eligible recyclable materials. The study used directly measured household waste rather than self-reported intentions. This approach allowed the analysis to focus on actual sorting behavior and on the quantity of inorganic waste separated by households.

The results show that all three interventions were positively associated with household waste sorting after differences in household, housing, socioeconomic, and waste-service characteristics were taken into account. The integrated intervention that combined facilities, education, collection support, and monetary incentives produced the strongest effect. The provision of facilities produced the second-largest effect, while the education-based intervention produced the smallest but still significant effect. These findings show that household sorting is shaped by physical opportunity, practical capability, and perceived benefits. They also confirm that household sorting is an important upstream condition for an effective circular economy.

5.2 Implications

For policymakers and regulators, the findings support a layered approach to household waste policy. Waste-sorting programs should not rely only on awareness campaigns or the distribution of bins. Facilities must be supported by clear instructions, regular collection, and a system that keeps recyclable and residual waste separated after collection. Monetary incentives may be useful for generating an immediate response, but they should be used together with practical education and reliable services. Policies should also consider differences in income, housing conditions, storage capacity, and the person who directly handles household waste. A single intervention is unlikely to produce the same result across all communities.

For waste-management providers, service performance should be assessed through outcomes, not only through the amount of waste collected or transported. Regulators should set key performance indicators that measure the quantity and proportion of recyclable waste separated at source, residual mixed waste per capita, contamination in the recyclable fraction, collection reliability, and the preservation of separated waste during transport and further handling. Providers should also be evaluated on whether household sorting efforts are maintained throughout the downstream system. These indicators would create a stronger link between household participation, service quality, recycling performance, and circular-economy objectives.

5.3 Limitations

The findings should be interpreted with caution. The observation period was short, and the household sample was limited. The groups also differed in total waste generation, inorganic waste composition, disposal frequency, housing characteristics, and other household conditions. Although the regression models controlled for several observable differences, these baseline variations may still affect the estimated results. The main outcome was also measured in absolute kilograms, which may be influenced by the amount of recyclable material available in each household. Future analysis may therefore also use per-capita indicators and separation ratios.

The study also cannot determine whether the observed changes would continue after the interventions were

withdrawn. In particular, the strong response to monetary incentives should not be interpreted as evidence of long-term behavioral persistence. The educational component was delivered only once, so the results do not show whether repeated and practical education would produce stronger effects over time. In addition, the relationship between income and socioeconomic stratum should be examined carefully because the two variables may capture overlapping household characteristics. These limitations restrict broad generalization, but they do not change the main finding that coordinated and context-sensitive interventions are more effective than isolated measures.

ACKNOWLEDGMENT

This research was supported by the Directorate of Research and Innovation Funding, National Research and Innovation Agency (BRIN) under Grant No. 110/IV/KS/11/2023. The authors gratefully acknowledge the National Research and Innovation Agency (BRIN), particularly the Research Center for Behavioral and Circular Economy, for coordinating the research activities. We also thank Universitas Pembangunan Nasional "Veteran" Jakarta, Universitas Hasanuddin, Universitas Islam 45 Bekasi, KIBUMI, and IPB University for their collaboration and technical support. Our sincere appreciation is extended to the participating households, community leaders, local governments in Depok and South Tangerang, and all field enumerators for their invaluable contributions to the successful completion of this study.

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