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# Abstract

Efficient waste management remains a critical challenge in developing countries, where rapid urbanization, population growth, and increasing consumption patterns are accelerating waste generation, while the high potential for processing organic waste is often undermined by limited segregation at the source. Building on prior experimental evidence from Mymensingh, this study evaluates a randomized intervention implemented in Cox's Bazar Municipality, covering 417 households across 76 clusters. The intervention combines infrastructure provision, information, and system-level linkages to improve waste segregation practices. It includes enhanced source-segregation infrastructure, such as distribution of color-coded bins at the household level and large collection drums at the cluster level, alongside the provision of information on wet and dry waste separation. In addition, the intervention establishes regular linkages between waste collectors and both formal and informal recycling markets within the waste value chain. Waste collectors gathered segregated waste from each cluster every two days, after which recyclable dry waste was transported to informal recycling markets for recovery and resale, while organic wet waste was delivered to a Black Soldier Fly (BSF) larvae production farm for processing and bio-conversion. Findings demonstrate a substantial shift in waste management behaviours, particularly in the utilization of infrastructure and participation in recycling markets. Daily disposal of waste in designated large drums increased by 24.1 percentage points (adjusted intention-to-treat [ITT] = 0.241, $p < 0.01$), while the likelihood of households selling recyclable materials rose by 14.7 percentage points (adjusted ITT = 0.147, $p < 0.01$). Most notably, the separation of wet and dry waste into different drums increased by 25.1 percentage points (adjusted ITT = 0.251, $p < 0.01$). Although positive trends were also observed in daily disposal practices and organic composting, the results consistently highlight that access to appropriate physical infrastructure plays a decisive role in overcoming structural barriers to waste segregation in tropical urban settings like Cox's Bazar Municipality. Furthermore, system-level integration with collection services is critical to sustaining household-level behavioural change. The findings suggest that urban waste management policies in developing countries should move beyond awareness campaigns and prioritize investments in accessible, user-friendly segregation infrastructure at both household and community levels. Municipal authorities should integrate provision of color-coded bins for waste segregation and cluster-based collection systems into standard service delivery models, ensuring regular and reliable sorted waste collection. Scaling such infrastructure-led, system-integrated approaches can significantly enhance waste recovery, reduce negative environmental externalities, and support the development of a circular economy in rapidly urbanizing contexts.



***Keywords:*** *Solid waste management, Randomized controlled trial, Infrastructure-led intervention, Waste-to-energy; Urbanization*

# 1. Introduction

Conventional urban waste management practices in many Low- and Middle-Income Countries (LMICs), including Bangladesh, have reached a critical impasse. Historically, these systems have relied on “collect-and-dump” models that are inherently unsustainable, contributing to severe environmental degradation and escalating public health risks. Beyond their ecological impacts, such traditional approaches fail to recognize the significant economic potential of waste as a reusable resource within a “waste-to-wealth” framework.

A major limitation of conventional waste management systems is the absence of source-sorting at the household level. When organic, recyclable, and hazardous wastes are mixed together, the opportunities for composting, recycling, energy recovery, and resource valorization become substantially reduced. Source-sorting is therefore a critical first step toward establishing an efficient circular economy, as it improves waste recovery, reduces landfill dependency, lowers greenhouse gas emissions, and enhances the feasibility of decentralized waste treatment systems.

In Bangladesh, rapid urbanization, population growth, and economic expansion are accelerating daily waste generation. Consequently, transitioning from a linear “collect–transport–dispose” system to a circular economy approach has become increasingly essential for achieving sustainable urban resilience, particularly in environmentally vulnerable and tourism-dependent coastal areas such as Cox’s Bazar. In this context, promoting household-level source-sorting practices can play a transformative role in improving municipal waste management, reducing environmental pollution, and creating opportunities for green enterprises and sustainable livelihoods.

Cox’s Bazar presents a particularly complex waste management context due to its high population mobility, tourism-driven economic activity, and additional pressure from the large Rohingya refugee population. These combined factors have substantially increased the volume of municipal waste, placing significant strain on existing waste management systems and municipal service capacity.

In this context, the project explored innovative and market-oriented approaches to enhance the value recovery potential of domestic waste through household source-sorting and resource utilization pathways. By examining how segregated waste can serve as a feedstock for composting, recycling, and other circular economy initiatives, the project aimed to identify practical strategies for transforming urban waste from an environmental burden into an economic resource.

To strengthen the local value chain, the project established a collaborative network involving representatives from Cox’s Bazar Municipality and a specialized local social enterprise such as DYADIC. The enterprise utilises organic waste through innovative bio-conversion processes to produce insect-based poultry and fish feed. By linking households, waste collectors, and recycling businesses within a coordinated system, the project sought to improve the efficiency and profitability of both wet and dry waste processing while supporting decentralized “waste-to-wealth” solutions.

The core of the evaluation was designed as a Cluster Randomized Controlled Trial (cRCT). Improved waste sorting facilities and behavioral interventions were provided to treatment clusters, while control clusters continued with existing waste management practices. This design enabled the study to systematically assess the extent to which improved infrastructure and community engagement influence household source-sorting behavior and waste recovery rates. The findings are expected to provide evidence-based guidance for policymakers and municipal authorities in Cox's Bazar and other urban settings on how to reduce environmental impacts, strengthen circular economy practices, and encourage greater private sector participation in sustainable waste management systems.

A significant contribution of this experiment, and a key departure from previous literature, is the rigorous measurement of waste at the source throughout the study period. Earlier studies in similar settings have primarily relied on self-reported information or visual estimations of waste generation and segregation practices, both of which are susceptible to substantial reporting and observer bias. In contrast, this project implemented a systematic waste measurement protocol in which sorted and unsorted waste were physically weighed at the aggregate level across treatment and control clusters.

This granular and objective dataset enables a more accurate estimation of waste recovery rates, segregation efficiency, and the economic feasibility of processing larger volumes of sorted waste relative to the costs of providing source-sorting infrastructure. As a result, the project not only contributes to the evidence base on household waste segregation behavior, but also generates practical insights into the operational and financial viability of decentralized circular economy interventions in urban Bangladesh.

# 2. Literature Review

### 2.1 Urban Waste Management Challenges in Bangladesh

Bangladesh has experienced a rapid increase in municipal waste generation over recent decades. Earlier estimates suggested that the six major cities of Bangladesh generated approximately 8,000 tons of solid waste daily, with Dhaka alone accounting for nearly 70% of total waste generation (Abedin & Jahiruddin, 2015). More recent estimates indicate that urban centres collectively generate approximately 23,688 tons of waste per day, of which nearly 70% consists of organic solid waste (Alam & Qiao, 2020). Importantly, around 66% of this organic waste is compostable in nature (Sujauddin et al., 2008), suggesting considerable potential for composting and biological waste recovery.

Plastic waste also represents a growing environmental concern. Household waste is now one of the largest contributors to plastic pollution, with approximately 646 tons of plastic waste generated daily (Abdullah & Abedin, 2024). However, only around 10% of plastic waste is currently recycled, while more than one-third is improperly disposed of. Poor waste management practices contribute substantially to greenhouse gas emissions, environmental contamination, and public health hazards. Existing estimates suggest that municipal waste in Bangladesh generates approximately 250.96 million tons of methane ($CH_4$), while substantial economic gains could be achieved through methane recovery, recycling, and composting initiatives (Shams et al., 2017; Alamgir,M. & Ahsan, 2007).

Current waste management systems in Bangladesh largely follow a conventional "collect-and-dump" model. Households typically store mixed waste in a single container, which is later collected and transported to secondary dumping sites and final disposal locations. However, municipal collection systems frequently suffer from inadequate infrastructure, limited staffing, poor coordination, and insufficient collection capacity. Studies indicate that only about 50% of waste generated in Dhaka and Chittagong is effectively collected and disposed of (Hasan, 1998), while approximately 55% of urban waste remains uncollected nationwide (Islam, Sirajul, 2021). In Cox's Bazar Municipality alone, nearly 0.3 million tons of waste have accumulated in open dumpsites since 2010, creating risks of environmental contamination and leachate pollution.

These challenges are expected to intensify in the future. Municipal solid waste in Bangladesh is projected to increase dramatically by 2050, while climate-related environmental risks associated with unmanaged waste will continue to grow. Consequently, there is increasing recognition that Bangladesh requires more sustainable and decentralized waste management systems that incorporate recycling, composting, and resource recovery approaches.

### 2.2 Importance of Household Source-Sorting

Within the broader waste management system, household-level source-sorting has emerged as a critical prerequisite for effective recycling and waste recovery. Source-sorting refers to the separation of waste into categories such as biodegradable and non-biodegradable materials at the point of generation. Without reliable segregation at the household level, the economic and environmental potential of downstream recycling and composting systems becomes substantially reduced.

Community-based waste segregation systems that begin at the household level can improve collection efficiency, facilitate recycling and composting, reduce contamination, and support decentralized "waste-to-wealth" initiatives (Yasmin, 2017). Source-sorting also enables organic waste to be converted into compost, biochar, biogas, or animal feed inputs, thereby reducing greenhouse gas emissions and environmental pollution. Studies suggest that recycling organic waste through composting and biochar production could significantly reduce emissions of $CO_2$, $CH_4$, $N_2O$, and $NH_3$ (Mia et al., 2018).

Despite these potential benefits, household participation in source-sorting remains limited in many urban areas due to behavioural, infrastructural, and institutional barriers. This has led researchers and policymakers to explore interventions aimed at encouraging sustained waste segregation practices among urban households.

### 2.3 Theoretical Frameworks Explaining Waste Segregation Behaviour

Several behavioural theories help explain household waste segregation practices. One of the most widely used frameworks is the Theory of Planned Behaviour (TPB), which posits that behaviour is influenced by attitudes, subjective norms, and perceived behavioural control. In the context of waste segregation, TPB suggests that households are more likely to sort waste when they perceive environmental benefits, believe that segregation is socially expected, and feel capable of performing the behaviour correctly.

Agent-Based Modelling (ABM) extends this perspective by examining how individual household behaviours evolve within broader social and policy environments. Using TPB-informed ABM simulations, Ma et al. (2023) demonstrate that while monetary incentives can improve participation in waste classification, combinations of policies tend to produce stronger outcomes than isolated interventions.

Additional behavioural frameworks such as the Motivation–Opportunity–Ability–Behaviour (MOAB) model and the Yale model of persuasive communication further highlight the importance of practical opportunities, infrastructure, communication methods, and behavioural messaging in shaping waste segregation practices. These frameworks suggest that even environmentally motivated households may fail to segregate waste when appropriate infrastructure, information, or institutional support is absent.

### 2.4 Evidence from Existing Waste Segregation Interventions

#### Informational Interventions

Informational interventions are among the most widely studied approaches for promoting household waste segregation. These interventions generally aim to improve environmental awareness, clarify segregation procedures, and encourage pro-environmental behaviour through educational materials, awareness campaigns, and community engagement.

A systematic review by Trushna et al. (2024) found that informational interventions were the most commonly implemented and often among the most effective approaches for improving household waste segregation behaviour. Evidence from Indonesia, Nepal, and Sri Lanka suggests that information campaigns, community monitoring, leaflets, and sensitization activities can positively influence waste disposal and segregation practices (Murase et al., 2017; Nepal et al., 2022; Pallegedara et al., 2024). However, the literature also suggests that information-only interventions frequently produce modest effects unless combined with infrastructure or incentive-based strategies.

#### Infrastructure-Based Interventions

Physical infrastructure and convenience are consistently identified as major determinants of source-sorting behaviour. Studies indicate that households are more likely to segregate waste when they are provided with accessible, appropriately sized, and easy-to-use bins or sorting systems.

Research from Sweden, Bhutan, Mozambique, Sri Lanka, and Bangladesh demonstrates that the provision of bins, colour-coded sorting systems, and household sorting equipment significantly improves segregation outcomes (Bernstad, 2014; Dutta-Powell et al., 2023; Hosono & Aoyagi, 2018; Wadehra & Nie, 2023). In Dhaka, studies have shown that the overwhelming majority of households lack adequate sorting infrastructure, particularly in high-rise residential settings (Atiq Uz Zaman, 2014). These findings suggest that infrastructural barriers often limit the effectiveness of informational campaigns alone.

#### Financial and Incentive-Based Approaches

A separate body of literature examines financial incentives such as Pay-As-You-Throw (PAYT) systems and monetary or in-kind rewards. PAYT systems charge households based on the volume of unsorted waste they dispose of, thereby encouraging recycling and segregation. Evidence from Italy suggests that PAYT can substantially increase sorted waste ratios, although implementation challenges and spillover effects may arise (Bucciol et al., 2015).

Studies from Ghana and Mozambique also show mixed evidence regarding the relative effectiveness of cash incentives, non-cash rewards, and infrastructure provision (Owusu et al., 2013; Hosono & Aoyagi, 2018). Overall, the literature suggests that combinations of informational, infrastructural, and incentive-based interventions are often more effective than single-component strategies.

**Behavioural Spillovers**

An important area of research concerns behavioural spillovers, whereby participation in one pro-environmental activity may influence other environmentally relevant behaviours. Evidence from Sweden suggests that participation in organic waste sorting programs can reduce overall household waste generation and improve other recycling behaviours, although such effects may diminish over time (Alacevich et al., 2021; Miliute-Plepiene & Plepys, 2015). These findings highlight the broader behavioural implications of waste segregation interventions beyond their immediate objectives.

**Evidence from Bangladesh**

Evidence from Bangladesh remains relatively limited compared to high-income settings. Existing studies suggest that urban residents are generally willing to participate in improved waste management systems and may even be willing to pay additional fees for enhanced services (Afroz et al., 2009; Afroz, 2011).

A cluster RCT conducted in Mymensingh found that informational interventions combined with bin provision substantially increased household segregation rates compared to information-only interventions (Wadehra & Nie, 2023). However, relatively few rigorous experimental studies have been conducted in highly urbanized and environmentally vulnerable municipalities such as Cox's Bazar.

### 2.5 Research Gaps

Despite the growing literature on household waste segregation, several important gaps remain. First, there is limited experimental evidence from Bangladesh and other LMICs experiencing rapid urbanization, tourism-related pressures, and refugee-related demographic changes (Table 1). Second, many existing studies rely heavily on self-reported behaviours or periodic audits, both of which are vulnerable to reporting bias and measurement limitations.

Continuous, weight-based measurement of sorted waste remains relatively uncommon despite offering important methodological advantages. Such objective approaches enable researchers to assess not only whether households segregate waste, but also the quantity of waste sorted, the speed of behavioural adoption, seasonal variation, and the persistence or decay of intervention effects over time.

**Table 1: Relevant studies**

| Theme | Intervention | Country studied | Evaluation methods (RCT, Observational) | Source |
|---|---|---|---|---|
| Infrastructure and non-financial incentive | Exchange of household goods, distribution of buckets, periodic home visit instruction | Mozambique | RCT, 3 Treatment Groups | (Hosono, T., & Aoyagi, K., 2018). |
| Information and Infrastructure Incentive | Distribution of written information amongst household and installation of equipment aiming at increasing convenience for source-segregation of household food waste inside the household. | Malmö, Sweden | Repeated Treatment Design | (Bernstad, A., 2014) |
| Information and Infrastructure Intervention | Distribution of bins with stickers explaining what items went in each bin, distribution of bins with stickers along with feedback on mistakes made by participants | Changzamtog, Thimphu, Bhutan | RCT, 2 Treatment Groups | (Dutta-Powell, R., Court, C., & Clark, A., 2023) |
| Information and Infrastructure Intervention | Distribution of information through pamphlets, posters, | Bharatpur, Nepal | Cluster RCT | (Nepal, M., et al., 2022). |

| Theme | Intervention | Country studied | Evaluation methods (RCT, Observational) | Source |
|---|---|---|---|---|
| | sensitization workshops for executive committee members of the TLOs and households and installation of 20L street waste bins for Community use. | | | |
| Information and Infrastructure Intervention | Brochures informing the option of having an additional bin dedicated to organic waste, the costs for ach possible bin combination, the distribution date of these bins and distribution of the bins | Partille Municipality, Sweden | Staggered DiD from natural experiment triggered by the staggered implementation of a policy | (Alacevich, C., Bonev, P., & Söderberg, M., 2021) |
| Information Intervention | Awareness raising activities which include: (1) monitoring of waste stations by environmental volunteers during designated weeks (2) feedback meetings between environmental volunteers and city government officers to share the results of the monitoring; and (3) consultation meetings between environmental volunteers and residents of each RT to discuss issues based on the results of the feedback meetings. | Balikpapan City, Indonesia | Cluster RCT | (Murase, N., Murayama, T., Nishikizawa, S., & Sato, Y., 2017). |
| Financial and non-financial Incentive | Cash incentive - US$ 1.9, US$ 1.49, US$ 2.49 and noncash incentive - provision of free solid waste bins to the households in exchange to participating in waste segregation | Kumasi metropolis, Ghana | Cross Sectional Survey | (Owusu, V., Adjei-Addo, E., & Sundberg, C., 2013) |

| Theme | Intervention | Country studied | Evaluation methods (RCT, Observational) | Source |
|---|---|---|---|---|
| Information and Infrastructure Intervention | Distribution of information leaflets regarding proper waste management at household level and information brochure along with distribution of three-color coded bins | Bulagala, Dambulugama, Dambulla, Yapagama wards, Sri Lanka | RCT, 2 Treatment Groups | (Pallegedara, A., Sisira Kumara, A., Jayasena, D. M., & Soysa, R. N. K., 2024). |
| Financial Intervention | Pay As You Throw Scheme - households charged by volume of residual waste | Municipalities of Treviso district, Italy | Panel Data | (Broer, K.H., 1976) |
| Information and Infrastructure Intervention | Distribution of information brochure introducing segregation to organic and non-organic waste, distribution of information brochure along with a dustbin, distribution of information brochure along with plastic bags to be used as garbage bags | Mymensingh, Bangladesh | Cluster RCT, 3 Treatment Groups: | (Wadehra and Nie, 2023) |

### 2.6 The Present Study

The present study addresses the contextual research gaps through the implementation of a Cluster Randomized Controlled Trial (cRCT) in Cox's Bazar Municipality. The intervention combines household bin provision, informational materials, and specifically framed behavioural messaging to examine their effects on household waste segregation practices.

A major methodological contribution of the study is the use of continuous daily weight-based measurement of wet and dry waste collected from treatment and control clusters. This objective and granular measurement strategy improves the accuracy and credibility of the findings while enabling detailed analysis of behavioural adoption and waste recovery dynamics over time.

By generating evidence from a highly pressured urban context in Bangladesh, the study contributes both locally relevant policy insights and broader methodological lessons for designing and evaluating waste segregation interventions in LMIC settings.

# 3. Methodology

## 3.1 Study site selection

The study site selection will focus on Ward 5 of Cox's Bazar Municipality (Figure 1), which was chosen for its logistical feasibility. This ward, with a population of 12,303 residents across 2589 households within 461 acres, represents a relatively densely populated residential area. This location was selected due to its proximity to both the Cox's Bazar Paurashava dumpsite and the implementer's field office, facilitating efficient waste collection, weighing, and data recording. While Ward 12 and Ward 1 are also large wards with ongoing waste management projects by other NGOs (BRAC and a local NGO), Ward 5 was prioritized to avoid potential interference with existing interventions and to ensure the independent evaluation of the current study's impact.

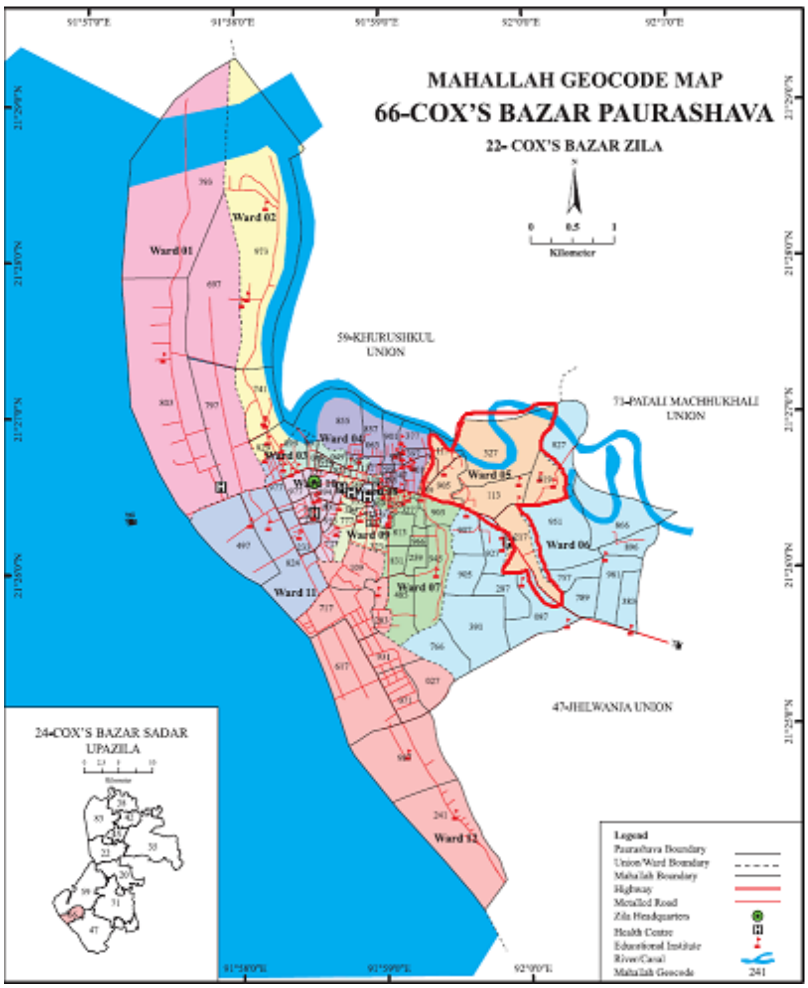



**Figure 1. Study Site: Ward 5 (marked with a thick red line) in the Cox's Bazar Municipality Map (BBS, 2024, p.31)**

## 3.2 Evaluation Design

This study employed a clustered randomized controlled trial (RCT) design. We will map the target areas to create 80 clusters, with groups of 5-6 neighbouring houses in each cluster, in selected wards of Cox's Bazar Municipality. Natural boundaries and landmarks will be used to create these clusters so that garbage collection, transportation, and measurement can be done with proper identification for each cluster. These clusters will be randomly assigned to either a treatment group (40 clusters) or a control group (40 clusters). In the treatment groups, the household head as well as the key person who manages household waste (such as a housemaid) will be given information about the initiative, awareness about the environmental benefits of sorting, and a bin for separating dry (organic) vs. wet (inorganic) waste with financial incentives (Figure 2).

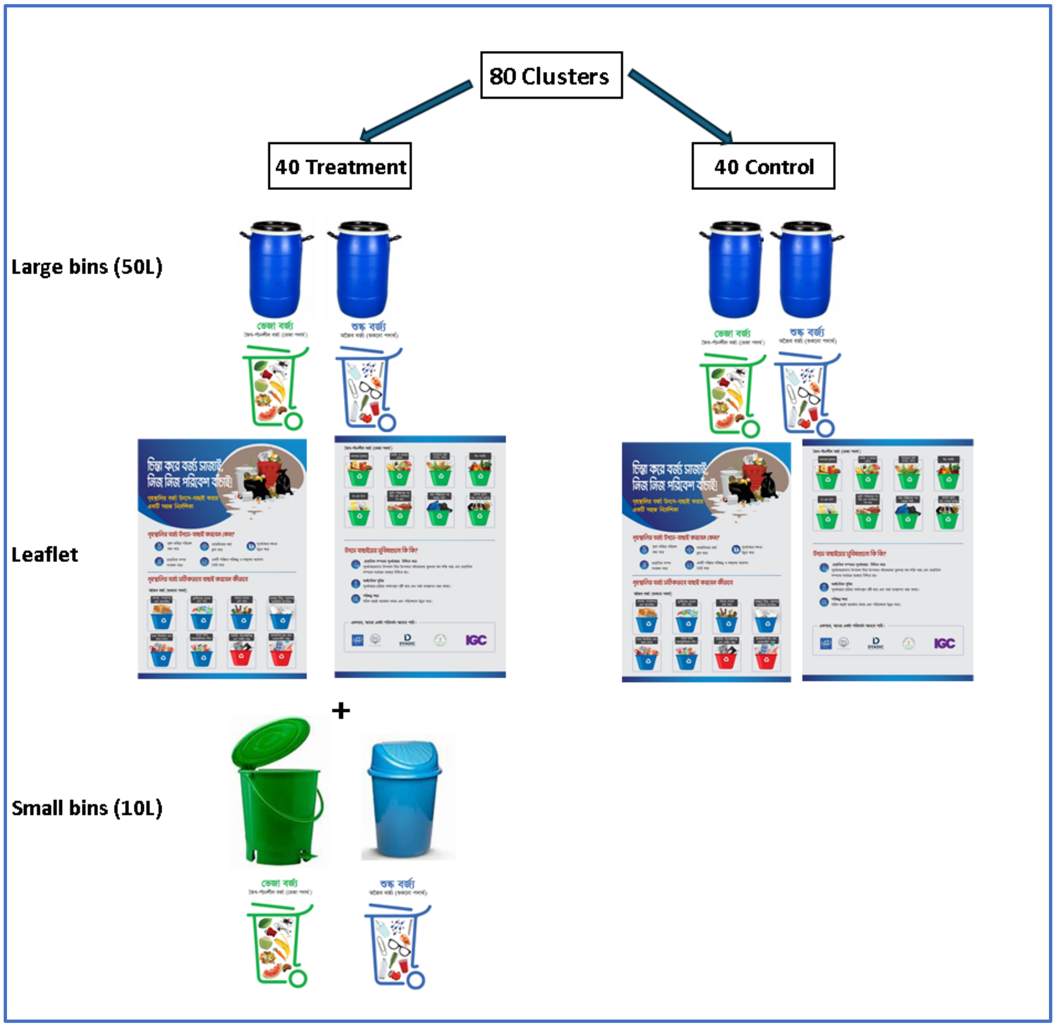



**Figure 2. Intervention designing at a glance**

## 3.3 Theory of Change

**Problem Statement:** Prior to the intervention, most households in Ward-5 of Cox's Bazar Paurashava disposed of waste without separating organic and inorganic materials. This was largely due to limited awareness of waste categories, lack of convenient sorting tools, and absence of structured household-level waste management systems. As a result, mixed waste disposal was common, leading to inefficient municipal waste collection, reduced recycling opportunities, and increased environmental pollution. These challenges highlighted the need for a household-level intervention that could simultaneously address knowledge gaps and infrastructure constraints.

**Intervention Inputs:** The intervention introduced both physical infrastructure and educational materials to enable waste segregation at source. Households in treatment clusters received two large outdoor bins (50 litres each) designated for organic and inorganic waste, along with two smaller indoor bins (10 litres each) intended for use in kitchens or other waste-generation areas. In addition to these materials, illustrated educational leaflets were distributed to explain proper waste sorting practices and demonstrate the types of waste suitable for each bin category. These inputs were designed to remove logistical barriers and increase household awareness of correct waste management practices.

**Intervention Activities:** The intervention focused on distributing sorting materials and promoting proper waste separation practices among households. Households were encouraged to use the small indoor bins for daily waste generation and transfer the contents into the larger outdoor bins for storage prior to collection. Educational leaflets supported this process by reinforcing correct sorting behaviour and providing visual guidance. These activities were intended to create consistent sorting routines within households and promote correct waste classification at the source.

**Immediate Outputs:** The immediate outputs of the intervention included increased availability of waste-sorting infrastructure at the household level and improved understanding of waste segregation practices. Households began using separate bins for organic and inorganic waste, leading to an observable reduction in mixed waste disposal. The distribution of leaflets ensured that households had accessible reference materials to support correct sorting practices. These outputs provided the foundation for behaviour change and system-level improvements.

**Short-Term Outcomes (Behavioural Change):** In the short term, the intervention is expected to produce measurable improvements in household waste sorting behaviour. Households that received bins and instructional materials are likely to develop routine sorting habits and demonstrate increased accuracy in waste separation. The use of indoor bins facilitates convenience and consistency, while outdoor bins provide adequate storage capacity. These behavioural changes are expected to reduce contamination between organic and inorganic waste streams and improve overall sorting quality.

**Intermediate Outcomes (System-Level Improvement):** As household sorting practices become consistent, the intervention is expected to improve municipal waste management processes. Segregated waste enables more efficient collection and facilitates the recovery of recyclable materials. Organic waste streams become easier to process through composting or alternative treatment methods. Reduced contamination also decreases the volume of waste requiring landfill disposal, improving operational efficiency and reducing environmental pressure on disposal sites.

**Long-Term Outcomes and Impact:** In the long term, the intervention is expected to contribute to improved environmental and public health outcomes. Sustained waste segregation practices are likely to lead to cleaner neighbourhoods, reduced environmental pollution, and improved urban sanitation conditions. Over time, these improvements support the development of more sustainable municipal waste management systems and enhance community awareness of responsible waste practices. Ultimately, the intervention aims to promote long-term environmental sustainability and improved quality of life within Ward-5 of Cox's Bazar Paurashava (Municipality) .

**Key Assumptions:** The effectiveness of this theory of change depends on several assumptions. It assumes that households are willing to adopt new waste management practices and consistently use the provided bins. It also assumes that the bins remain functional and accessible over time and that municipal waste collection systems are capable of handling segregated waste streams. Additionally, it assumes that educational materials are understandable and culturally appropriate for the target population.

**External Factors and Risks:** Several external factors may influence the success of the intervention. These include irregular waste collection services, damage or loss of bins, resistance to behavioural change and limited municipal enforcement of waste management practices. Socioeconomic conditions, population mobility, and seasonal variations may also affect household participation and consistency in sorting behaviour. Monitoring these external factors is important to ensure sustained effectiveness of the intervention.

Overall, the theory of change proposes that providing households with appropriate waste-sorting infrastructure and clear instructional guidance would encourage consistent waste segregation at the household level. This behavioural change is expected to improve waste collection efficiency, increase recycling potential, and reduce environmental pollution. Through sustained adoption of sorting practices, the intervention aims to create cleaner communities, strengthen municipal waste management systems, and support long-term environmental sustainability in Ward-5 of Cox's Bazar Paurashava.

## 3.3 The Model Specification

The impact of the intervention is estimated using a model (equation-1) that exploits the experimental design and the longitudinal structure of the data. Treatment was randomly assigned at the cluster level, which ensures that the treatment indicator ($Treat_c$) is exogenous. As a result, there is no selection bias at baseline, and treated and control clusters are statistically comparable prior to the intervention (discussed in results section).

Because random assignment ensures that treatment is orthogonal to household characteristics in expectation, we identify the intention-to-treat (ITT) effect by comparing post-intervention (endline) outcomes between treated and control households by using ANCOVA model (Equation 2).

Finally, since treatment assignment occurs at the cluster level, standard errors are clustered at the level of randomization. This accounts for intra-cluster correlation in outcomes and ensures correct statistical inference. Ignoring the clustered nature of the data leads to underestimated standard errors and an increased risk of Type I errors or rejecting a true null hypothesis. The p-values become smaller than they should be, leading researcher to claim a finding is "significant" when it might just be a result of group-level correlation.

$$Y_{ic} = \beta_0 + \beta_1 Treat_c + \varepsilon_{ic} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

**Adjusted model** with baseline covariates: covariates $(\gamma X_{ic})$: housing tenure (own/rented), salaried income status, sex of the waste disposer, household size, household ownership of multiple bins, and baseline waste sorting practices (yes/no).

$$Y_{ic} = \beta_0 + \beta_1 Treat_c + \gamma X_{ic} + \varepsilon_{ic} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

**Where:**

$i = household$
$c = cluster\ (randomization\ unit)$
$Y_{ict} = outcome$
$Treat_c = cluster\ assigned\ to\ treatment\ (1, 0)$
$X_{ic} = baseline\ control\ variables$
$\beta_1 = \boldsymbol{Intent-to-Treat\ (ITT)}\ effect$
$\varepsilon_{ic} = error\ term$

## 3.5 Data Collection

**Cluster selection:** In urban settings, each building was treated as one cluster for the study (unit of analysis). Building selection for the study involved a two-stage process. Initially, 100 potential buildings will be identified in collaboration with local municipality workers. This selection considered factors such as accessibility, the presence of multiple stories, and the number of households residing within each building. Subsequently, 81 buildings were shortlisted from this initial pool and added one more later. Finally, a randomized process was employed to assign 38 buildings to the Treatment Group and the remaining 38 to the Control Group, ensuring a balanced and unbiased distribution of participants across the two groups.

**Inclusion criteria:** Since the study area is an urban setting, the presence of semi-pakka, pakka, or kacha houses is expected to be minimal. However, to ensure consistency in our sampling approach, we included at least three storied buildings that have at least five households and exclude other types of housing structures. As a result, single-person households or those residing in semi-pakka, pakka, or kacha houses were not included in the study. Once data collection began, the research team carefully evaluated the selected buildings to ensure they meet the inclusion criteria.

**Baseline survey:** The study commenced with a baseline survey in May 2025, initially targeting 81 selected buildings to act as clusters, comprising 438 households, which averaged approximately five to six flats per building. Before moving forward, five buildings opted out of the study. This resulted in a final baseline cohort of 76 buildings and 417 households, which were then cluster-randomized into a Treatment Group and a Control Group for the intervention phase (Figure 3).

**Randomization and intervention:** The Treatment Group initially comprised 38 buildings and 210 households. Between July 14 and July 19, 2025, this group received an intervention consisting of two big drums and an informational leaflet. Shortly after, two buildings were dropped from the study because they returned the big drums, reducing the group to 36 buildings and 203 households. A second intervention phase occurred from September 13 to October 19, 2025, during which small bins, leaflets, and stickers were distributed. During this period, the study team removed 32 households that had relocated and 12 households that could not be reached, while simultaneously adding 103 households to the intervention that were not surveyed during the baseline. Following these adjustments and the small bin intervention, the Treatment Group consisted of 36 buildings and 262 households.

Meanwhile, the Control Group initially consisted of 38 buildings and 207 households. Following the same schedule as the first treatment phase, these households received a distribution of two big drums and a leaflet between July 14 and July 19, 2025. No further interventions or intermediate participant adjustments were recorded for the Control Group during this phase.

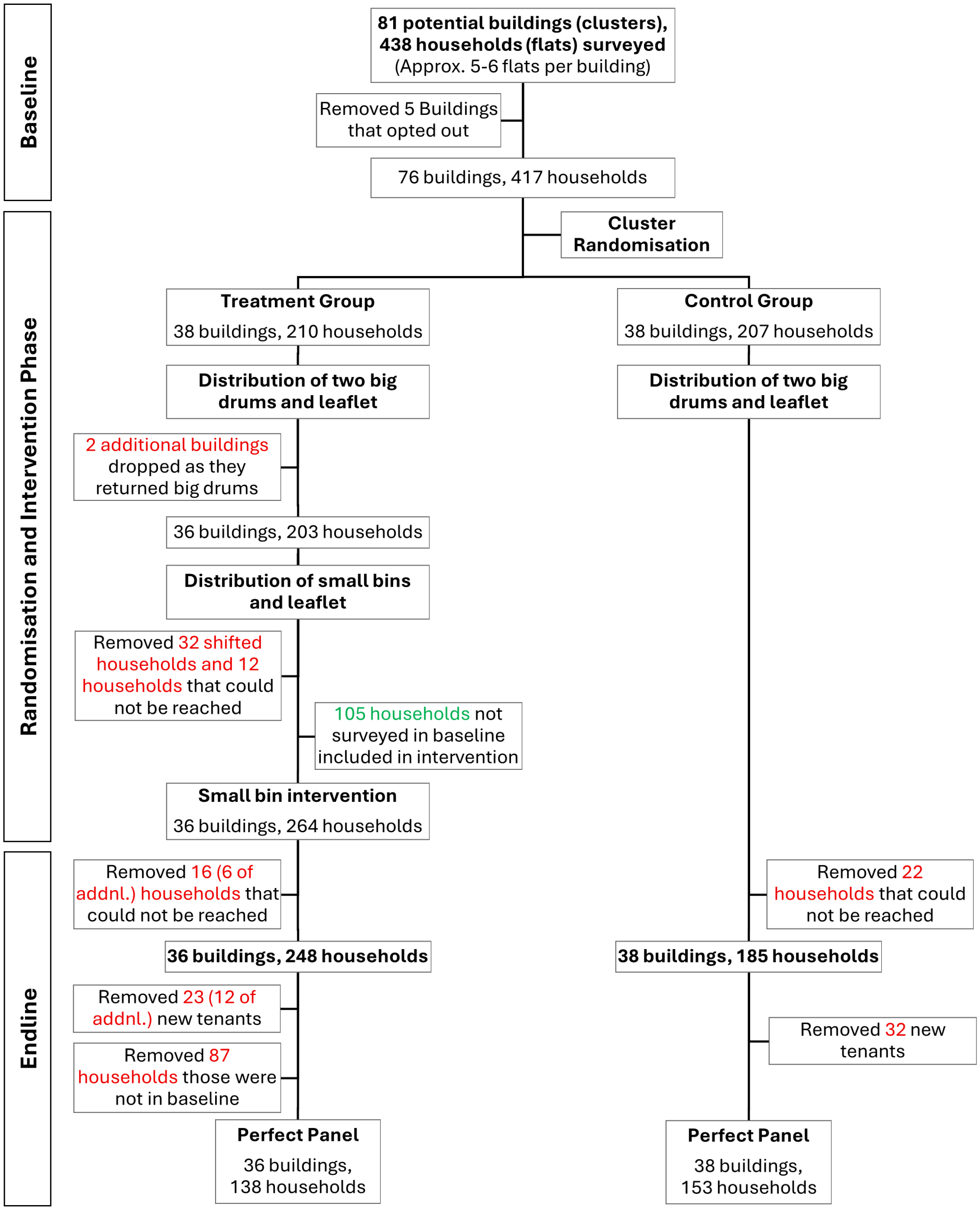



**Figure 3: Flow Diagram of Participant Clusters and Households from Baseline to Endline**

**Endline survey and final sample size:** The endline phase of the study took place in January 2026, focusing on establishing a "Perfect Panel" of households present for both the baseline and endline surveys. In the Treatment Group, 16 households were removed because they could not be reached, bringing the count to 248 households. To finalize the perfect panel, an additional 23 new tenants and the 87 remaining households that were not part of the original baseline were removed, resulting in a final Treatment panel of 36 buildings and 138 households. Concurrently, in the Control Group, 22 households were removed because they could not be reached, leaving 185 households. After excluding 32 new tenants, the final Control panel concluded with 38 buildings and 153 households (Figure 3).

# 4. Results

## 4.1 Descriptive Statistics

**Baseline Balancing:** To assess the success of the randomization process, a baseline balance test was conducted across 417 households (clustered within 76 units). As presented in Table 2, the results demonstrate that the treatment and control groups are statistically indistinguishable across all key dimensions, including socioeconomic characteristics, respondent demographics, and waste disposal behaviours. Notably, all calculated *p*-values are greater than 0.10 confirm a lack of systematic differences at the start of the study. For instance, fundamental variables such as per capita expenditure ($p = 0.615$) and waste sorting habits ($p = 0.230$) show strong parity. Furthermore, both groups exhibit a comparable level of baseline environmental awareness, as reflected by the Knowledge Index Score (Treatment Mean = 13.86; Control Mean = 14.13; $p = 0.133$). Additionally, the structural characteristics of the clusters, specifically the average number of flats per building, showed no statistical difference between the treatment (7.79) and control (7.84) groups (p=0.947). Consequently, any observed differences in post-intervention outcomes can be confidently attributed to the treatment rather than pre-existing variations.

**Table 2: Baseline Characteristics of Households in Treatment and Control**

| Variables | Treatment | | Control | | Total | | p-value |
|---|---|---|---|---|---|---|---|
| | N (Clusters) | Value | N (Clusters) | Value | N (Clusters) | Value | |
| **Waste Disposal Behaviour of Household** | | | | | | | |
| Household owns multiple bins | 210 (38) | 55.2% | 207 (38) | 53.6% | 417 (76) | 54.44% | 0.781 |
| Household disposes of waste daily | 210 (38) | 74.8% | 207 (38) | 71% | 417 (76) | 72.90% | 0.444 |
| **Waste Sorting Behaviour** | | | | | | | |
| Household sorts of waste | 210 (38) | 59.5% | 207 (38) | 53.6% | 417 (76) | 56.59% | 0.230 |
| Household ever sold recyclable waste | 210 (38) | 31.4% | 207 (38) | 25.1% | 417 (76) | 28.30% | 0.137 |
| Amount received by selling recyclable waste (last time), Mean (SD) | 66 (31) | 178.712 (297.208) | 52 (29) | 141.635 (164.364) | 118 (60) | 162.37 (271.96) | 0.391 |
| Total waste quantity sold last time (kg), Mean (SD) | 66 (31) | 6.712 (7.718) | 52 (29) | 6.308 (5.918) | 118 (60) | 6.533 (7.680) | 0.747 |

| Variables | Treatment | | Control | | Total | | p-value |
|---|---|---|---|---|---|---|---|
| | N (Clusters) | Value | N (Clusters) | Value | N (Clusters) | Value | |
| Household make compost with organic waste (unconditional) | 210 (38) | 25.2% | 207 (38) | 27.1% | 417 (76) | 26.14% | 0.713 |
| **Knowledge about waste sorting*** | | | | | | | |
| Knowledge Index Score, Mean (SD) | 210 (38) | 13.857 (1.841) | 207 (38) | 14.126 (1.790) | 417 (76) | 13.990 (1.502) | 0.133 |
| **Number of total flats per cluster** | | | | | | | |
| Number of total flats in the building, Mean (SD) | 296 (38) | 7.789 (3.129) | 298 (38) | 7.842 (3.723) | 594 (76) | 7.816 (3.416) | 0.947 |
| **Household Type** | | | | | | | |
| Own House | 210 (38) | 18.1% | 207 (38) | 20.8% | 417 (76) | 19.42% | 0.483 |
| Rented | 210 (38) | 74.8% | 207 (38) | 72.9% | 417 (76) | 73.86% | 0.686 |
| Care-taker | 210 (38) | 0% | 207 (38) | 0.5% | 417 (76) | 0.24% | 0.318 |
| Mess/Bachelor | 210 (38) | 6.7% | 207 (38) | 4.3% | 417 (76) | 5.52% | 0.384 |
| Office | 210 (38) | 0% | 207 (38) | 1% | 417 (76) | 0.48% | 0.165 |
| Madrasa | 210 (38) | 0.5% | 207 (38) | 0.5% | 417 (76) | 0.48% | 0.992 |
| **Respondent's characteristics** | | | | | | | |
| Age of the respondent, Mean (SD) | 210 (38) | 32.862 (11.974) | 207 (38) | 34.353 (10.509) | 417 (76) | 33.602 (10.526) | 0.178 |
| Sex of the respondent (Female) | 210 (38) | 77.6% | 207 (38) | 77.8% | 417 (76) | 77.70% | 0.972 |
| **Household characteristics** | | | | | | | |
| Households in Salaried Income | 195 (38) | 41.5% | 195 (38) | 41.5% | 390 (76) | 41.54% | 1.000 |
| Households with at least one member completing SSC or higher | 210 (38) | 86.7% | 207 (38) | 86% | 417 (76) | 86.33% | 0.827 |
| Households with at least one member completing HSC or higher | 204 (38) | 86.3% | 202 (38) | 85.6% | 406 (76) | 85.96% | 0.843 |
| Total household members (of all ages) | 210 (38) | 4.7 (5.352) | 207 (38) | 4.768 (5.436) | 417 (76) | 4.734 (5.015) | 0.897 |
| Number of earning members in the household, Mean (SD) | 210 (38) | 1.233 (0.933) | 207 (38) | 1.507 (3.941) | 417 (76) | 1.369 (2.806) | 0.331 |
| Per capita expenditure of household, Mean (SD) | 195 (38) | 11328.592 (6816.300) | 195 (38) | 10994.902 (6293.671) | 390 (76) | 11161.75 (5998.22) | 0.615 |
| The average daily meal count, Mean (SD) | 210 (38) | 12.286 (5.090) | 207 (38) | 12.913 (13.111) | 417 (76) | 12.597 (9.432) | 0.520 |
| **Waste Disposal Behaviour of Household** | | | | | | | |

| Variables | Treatment | | Control | | Total | | p-value |
|---|---|---|---|---|---|---|---|
| | N (Clusters) | Value | N (Clusters) | Value | N (Clusters) | Value | |
| Maids/Helping Hands Mostly Disposes Waste | 210 (38) | 13.8% | 207 (38) | 10.6% | 417 (76) | 12.23% | 0.370 |
| Municipal workers collect from designated containers inside the building | 210 (38) | 42.4% | 207 (38) | 25.6% | 417 (76) | 34.05% | 0.120 |
| Household pays charges for waste disposal service | 210 (38) | 26.2% | 207 (38) | 14% | 417 (76) | 20.14% | 0.117 |
| Paid amount for waste disposal service (in BDT), Mean (SD) | 55 (17) | 216.545 (244.438) | 29 (14) | 230.793 (244.438) | 84 (31) | 221.46 (203.58) | 0.818 |
| **Uses with recyclable waste (Conditional)** | | | | | | | |
| Reuse | 150 (38) | 56% | 139 (38) | 60.4% | 289 (76) | 58.13% | 0.565 |
| Sell or give away to recyclers | 150 (38) | 40.7% | 139 (38) | 36% | 289 (76) | 38.41% | 0.453 |
| **Willingness to participate in the study** | | | | | | | |
| Yes | 210 (38) | 97.6% | 207 (38) | 96.1% | 417 (76) | 96.88% | 0.443 |

***Note:** Knowledge Index Score: Calculated based on 16 questions. Each correct answer was assigned a value of 1, missing, or "don't know" responses were assigned 0, and while incorrect response was coded -1. The composite score ranges from -16 to 16, with no penalties for incorrect answers.

Table 3 reveals several significant differences between the treatment and control groups (panel data) at the end of the project. There are some direct impacts of the project's interventions. Most notably, the provision of waste management infrastructure is evident, as treatment households are significantly more likely to own multiple bins ($p<0.001$), likely a direct result of the small bin distribution, and are more aware of the two large drums installed in their building compound ($p = 0.001$). Consequently, a significantly higher proportion of treatment households reported using these large drums to dispose of waste daily over the past two weeks ($p = 0.004$). These physical interventions, paired with behavioural campaigns, successfully shifted habits: treatment households demonstrated a significantly higher propensity to actively sort their waste ($p<0.001$) and were much more likely to correctly dispose of wet and dry waste in separate drums ($p = 0.001$). The reach of the awareness interventions is also clearly reflected in the data, with treatment households being significantly more likely to have received educational leaflets or stickers ($p<0.001$) and to report being made aware of waste segregation and the harmful effects of pollution ($p = 0.09$). Finally, these improved practices appear to have positive spillover effects on recycling economics; treatment households were significantly more likely to have sold recyclable waste ($p = 0.009$), and when doing so, they sold a significantly larger quantity and received a higher monetary return not statistically significant though.

**Table 3: Comparison of Key Output and Outcomes Between Treatment and Control Groups at Endline**

| Variable | Treatment | | Control | | Total | | p-value |
|---|---|---|---|---|---|---|---|
| | N (Clusters) | Value | N (Clusters) | Value | N (Clusters) | Value | |
| **Waste Disposal Behaviour of Household** | | | | | | | |
| Household owns multiple bins | 138 (36) | 96.4% | 153 (38) | 54.9% | 291 (74) | 74.6% | <0.001*** |
| Household disposes of waste daily | 138 (36) | 70.3% | 153 (38) | 62.1% | 291 (74) | 66.0% | 0.187 |
| Household aware of two large drums installed in building compound | 138 (36) | 95.7% | 153 (38) | 76.5% | 291 (74) | 85.6% | 0.001*** |
| Household uses drums regularly | 132 (36) | 72.7% | 117 (37) | 60.7% | 249 (73) | 67.1% | 0.175 |
| Household disposed of waste in large drums daily in last two weeks | 138 (36) | 51.4% | 153 (38) | 28.1% | 291 (74) | 39.2% | 0.004*** |
| **Waste Sorting Behaviour** | | | | | | | |
| Household sorts of waste | 138 (36) | 81.9% | 153 (38) | 51.6% | 291 (74) | 66.0% | <0.001*** |
| Household dispose of wet and dry waste in separate drums | 110 (33) | 70.9% | 84 (29) | 44.0% | 194 (62) | 59.3% | 0.001*** |
| Household received any leaflets or sticker | 138 (36) | 66.7% | 153 (38) | 35.3% | 291 (74) | 50.2% | <0.001*** |
| Household made aware about waste segregation and harmful effects of pollution | 138 (36) | 63.8% | 153 (38) | 51.6% | 291 (74) | 57.4% | 0.090* |
| Household ever sold recyclable waste | 138 (36) | 40.6% | 153 (38) | 25.5% | 291 (74) | 32.6% | 0.009*** |
| Amount received by selling recyclable waste (last time), Mean (SD) | 56 (28) | 154.73 (181.29) | 39 (24) | 115.26 (76.91) | 95 (52) | 138.53 (153.75) | 0.151 |
| Total waste quantity sold last time(kg), Mean (SD) | 56 (28) | 6.27 (5.46) | 39 (24) | 5.13 (3.30) | 95 (52) | 5.80 (4.84) | 0.210 |
| Household make compost with organic waste (unconditional) | 138 (36) | 29.7% | 153 (38) | 22.2% | 291 (74) | 25.8% | 0.245 |
| **Knowledge about waste sorting** | | | | | | | |
| Knowledge Index Score | 138 (36) | 13.77 (1.29) | 153 (38) | 13.60 (1.26) | 291 (74) | 13.68 (1.27) | 0.266 |
| **Waste Disposal Behaviour of Household** | | | | | | | |
| Maids/Helping Hands Mostly Disposes Waste | 138 (36) | 15.9% | 153 (38) | 12.4% | 291 (74) | 14.1% | 0.473 |
| Municipal workers collect from designated container inside the building | 138 (36) | 84.1% | 153 (38) | 66.0% | 291 (74) | 74.6% | 0.047** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Household pays charges for waste disposal service | 138 (36) | 28.3% | 153 (38) | 14.4% | 291 (74) | 21.0% | 0.133 |
| Paid amount for waste disposal service (in BDT) | 39 (13) | 209.49 (316.54) | 22 (12) | 268.18 (149.14) | 61 (25) | 230.66 (263.98) | 0.331 |
| **Uses with recyclable wastes (Conditional)** | | | | | | | |
| Reuse | 123 (36) | 35.8% | 85 (32) | 32.9% | 208 (68) | 34.6% | 0.718 |
| Sell or give away to recyclers | 123 (36) | 43.1% | 85 (32) | 41.2% | 208 (68) | 42.3% | 0.788 |

**Note: *, **,** and *** indicates that the result is significant at the 10% level ($p < 0.10$), 5% level ($p < 0.05$), and 1% level ($p < 0.01$) respectively.

## 4.2 Impact Analysis

### 4.2.1 Attrition

Attrition represents the loss of participants between the baseline and endline phases of a study, which can potentially compromise the validity of the impact evaluation if not properly addressed. In this intervention, the total attrition rate was 30.2% (Table 4). The attrition was higher in the treatment group at 34.3% compared to 26.1% in the control group (Table 4). To determine if this loss of participants introduced systematic differences that could skew the results, an attrition bias analysis was conducted. The analysis of treatment groups in Column 1 shows a coefficient of 0.0820 with a p-value of 0.113, indicating that the difference in attrition rates between the treatment and control groups is not statistically significant at conventional levels (Table 5).

**Table 4: Attrition Rate based on Baseline Households**

| Household Status | Baseline | Endline | Attrition (%) |
|---|---|---|---|
| Treatment | 210 | 138 | 34.3% |
| Control | 207 | 153 | 26.1% |
| **Total** | 417 | 291 | 30.2% |

**Table 5: Attrition Bias Analysis**

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| Treatment Groups | 0.0820 | 0.0759 | -0.0196 |
| Standard Error | (0.0511) | (0.0497) | (0.118) |
| Observations | 417 | 417 | 417 |
| Covariates | No | Yes | Yes |
| Covariates x Treatment | No | No | Yes |
| F-stat (Treat + Interactions) | 2.570 | 2.333 | 0.0274 |
| p-value | 0.113 | 0.131 | 0.869 |

Furthermore, after adjusting for baseline covariates in Column 2, the p-value remains insignificant at 0.131, suggesting that observable household characteristics do not systematically predict attrition across the groups. The most rigorous test in Column 3, which includes interactions between covariates and the treatment status, yields a high p-value of 0.869, further supporting the lack of systematic bias. The overall lack of statistical significance across these tests in Table 4 indicates that while attrition occurred, it did not introduce a significant bias, suggesting that the remaining 291 households are still representative of the original randomized groups for a reliable estimation of the intervention's impact.

### 4.2.2 Intention-to-Treat (ITT) Effect

Table 6 presents the Intention-to-Treat (ITT) effect of the intervention on various household waste management practices, revealing significant behavioural shifts in specific areas. It reveals that the intervention led to substantial and meaningful changes in how households manage their waste, particularly regarding organization and recycling. The most prominent improvement occurred in waste segregation; households became much more likely to dispose of their wet and dry waste into separate containers, with the intervention group showing a 31 percentage point increase in this practice compared to the control group. This shift suggests that providing specialized facilities effectively encourages residents to sort waste at the source rather than mixing all types together.

In addition to better sorting, there was a significant increase in the consistent use of large disposal drums. Households in the treatment group were 24.1 percentage points more likely to use these drums for their daily disposal compared to those who did not receive the intervention. This indicates that when the right infrastructure is available and accessible, residents are willing to adopt more organized disposal routines.

**Table 6: Impact of the Intervention on Household Waste Management Practices**

| Outcomes | Obs. | Control Mean | Unadjusted ITT | Adjusted ITT |
|---|---|---|---|---|
| Household disposes waste daily (yes=1, no=0) | 291 | 0.621 | 0.082 (0.061) | 0.087 (0.062) |
| Household reuses recyclable waste (yes=1, no=0) | 291 | 0.183 | 0.136** (0.063) | 0.136** (0.061) |
| Household ever sold recyclable waste (yes=1, no=0) | 291 | 0.255 | 0.151*** (0.056) | 0.147*** (0.054) |
| Household makes compost with organic waste (yes=1, no=0) | 291 | 0.222 | 0.075 (0.064) | 0.073 (0.061) |
| Household disposes waste in big drums daily (yes=1, no=0) | 291 | 0.281 | 0.233*** (0.078) | 0.241*** (0.075) |
| Household disposes wet and dry waste in separate drums (yes=1, no=0) | 291 | .242 | 0.323*** (0.070) | 0.310*** (0.067) |

**Note: *, **,** and ***** indicates that the result is significant at the 10% level ($p < 0.10$), 5% level ($p < 0.05$), and 1% level ($p < 0.01$) respectively. The standard errors are shown within parentheses.

The study also highlights a positive impact on the local circular economy. Households that received the intervention were 14.7 percentage points more likely to sell their recyclable materials rather than simply discarding them. While there were slight increases in other behaviours, such as composting organic waste and general daily disposal, the primary successes of this program were clearly cantered on rigorous waste segregation and the financial incentivization of recycling through the sale of materials.

### 4.2.3 System Level Change

The intervention's system-level impact is characterized by a notable shift in waste disposal volumes following the introduction of reliable daily collection services and household-level sorting tools. By ensuring consistent collection, every two days from each cluster, the system effectively encouraged households to participate more actively in the waste management cycle.

**Organic (wet) waste collection:** The overall system performance improved significantly, with most of the collected material consisting of biodegradable organic or wet waste. Data from Table 7 reveals a clear divergence in disposal behaviour between the two groups: Treatment households disposed of more waste on average than those in the control group. Treatment households averaged 1.36 kg of waste per day, compared to 1.29 kg for control households. This difference was statistically significant, indicating that the combination of daily collection and color-coded bins successfully captured more waste within the formal system.

**Inorganic (dry) waste collection:** While total waste disposal increased significantly, patterns for dry waste, which includes recyclables, remained more volatile over the intervention period. For instance, the treatment households collected an average of **8.51 grams** of dry waste per day, while control households averaged **7.50 grams**. Although the treatment group showed a slightly higher average, Table 8 indicates this specific difference was not statistically significant.

**Table 7: Comparison of Average Waste Collected per Household by Group over Time**

| Group | Observation (n) | Average Waste per HH per day (kg) | Standard Error | t-statistic | p-value |
|---|---|---|---|---|---|
| Treatment | 69 | 1.36 | 0.037 | **2.542** | **0.013** |
| Control | 69 | 1.29 | 0.027 | | |

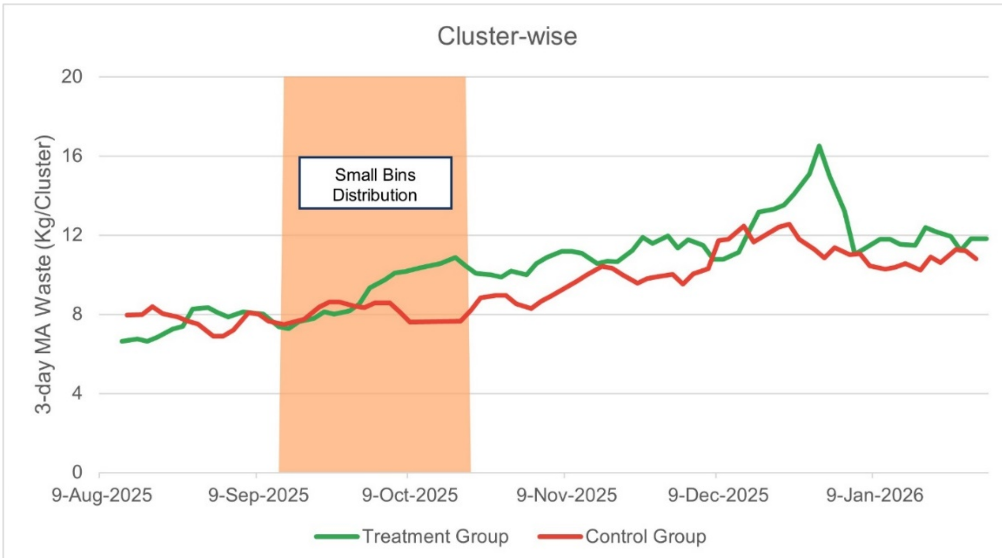
**Table 8: Comparison of Average Dry Waste Collected per Household by Group over Time**

| Group | Observation (n) | Average Dry Waste per HH per day (grams) | Standard Error | t-statistic | p-value |
|---|---|---|---|---|---|
| Treatment | 69 | 8.51 | 0.82 | **1.07** | **0.289** |
| Control | 69 | 7.50 | 0.89 | | |

This suggests that while the system was highly effective at capturing organic waste, dry waste disposal remained relatively similar between groups, potentially due to households choosing to sell high-value recyclables rather than disposing of them through the collection service.

Households retain dry waste for later sale to the informal scrap-buyers (locally known as '*Bhanggari*').

Trends visualized in Figure 4 and Figure 5 show that the divergence in waste disposal often became most apparent following the distribution of color-coded bins (indicated by the shaded areas), suggesting that physical infrastructure at the household level is a key driver for maximizing the efficiency of cluster-level collection systems.



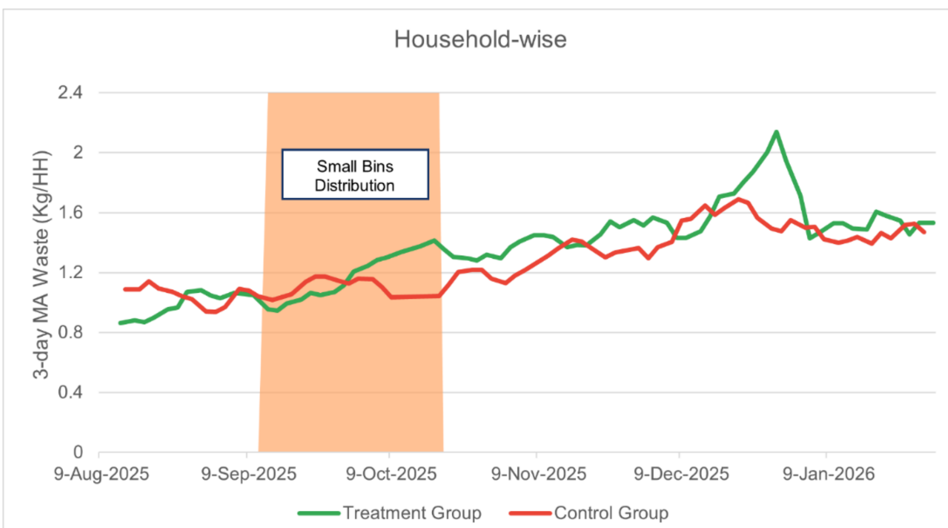




**Figure 4: Trends in Daily Waste Collection at Cluster and Household Levels**

**Notes:** The figure presents 3-day moving averages of waste collected from treatment and control clusters (or buildings). The shaded area indicates the period during which small, color-coded bins were distributed to treatment households. Large bins and daily waste collection services were provided to both treatment and control groups throughout the intervention period. The majority of collected waste consisted of biodegradable (organic/wet) waste.

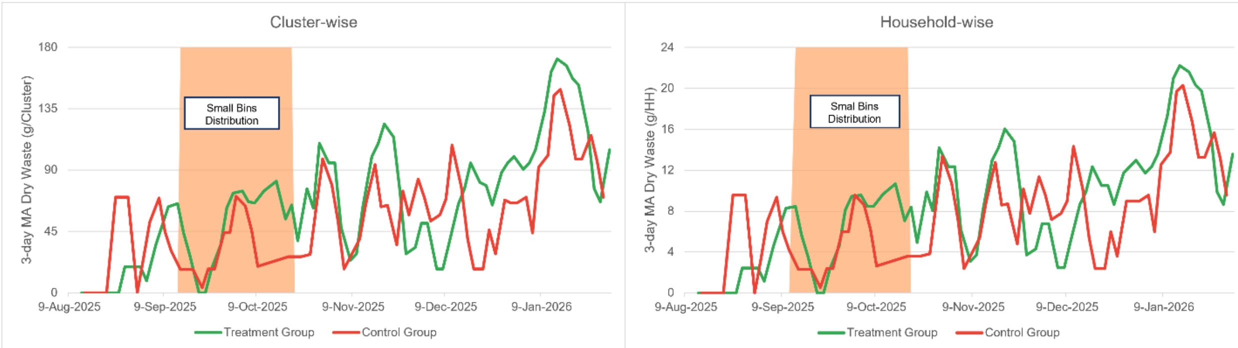



**Figure 5: Trends in Daily Dry Waste Collection at Cluster and Household Levels**

**Notes:** The charts illustrate the 3-day moving average (MA) of dry waste collection at both the cluster level (left, g/cluster) and household level (right, g/HH) between August 2025 and January 2026. The green line represents the treatment group, the red line represents the control group, and the shaded orange region indicates the timeline for small bin distribution.

### 4.2.4 Estimated reduction of carbon footprint

The waste management intervention demonstrated significant environmental and system-level impacts through improved household source-sorting, organic waste composting, and recyclable waste recovery. Compared with the control area, the treatment communities achieved substantially higher participation in waste segregation and recyclable waste selling, resulting in greater diversion of organic and recyclable waste from unmanaged disposal pathways. Table 9 shows that over the six-month intervention period (August 2025 to January 2026), the project reduced an estimated 6.43 tCO2e through bioconversion of organic waste at the Black Soldier Fly (BSF) farm and increased recycling of plastic and metal waste.

**Table 9: Calculation of reduction of $tCO_2e$**

| Sl | Indicator | Treatment | Control | Data Source |
|---|---|---|---|---|
| 1 | Total HH | 138 | 153 | Survey data |
| 2 | Daily Rate of Organic Waste (kg/HH) | 1.36 | 1.29 | Waste collection record data |
| 3 | Daily Rate of Recyclable Waste (g/HH) | 8.51 | 7.50 | Waste collection record data |
| 4 | Duration of Project (days) | 176 | 176 | |
| 5 | Proportion of HH participating in source-sorting | 0.565 | 0.242 | Endline survey data |
| 6 | **Total organic Waste Generated (kg)** | 18669.506 | 8399.436 | Row-1*Row-5*Row-2*Row-4 |
| 7 | **$tCO_2e$ avoided (organic composting at BSF Farm)** | **11.668** | **5.250** | Wastebits $CO_2$ Equivalents Calculator |

| Sl | Indicator | Treatment | Control | Data Source |
|---|---|---|---|---|
| 8 | Proportion of HH selling recyclable waste | 0.406 | 0.255 | Endline survey data |
| 9 | **Total Recyclable Waste Sold (kg)** | 83.916 | 51.500 | (Row-1*Row-8*Row-3*Row-4)/1000 |
| 10 | Proportion of Plastic Waste Sold | 0.416 | 0.515 | Endline survey data |
| 11 | Proportion of Metal Waste Sold | 0.193 | 0.025 | Endline survey data |
| 12 | **Total Plastic Sold (kg)** | 34.932 | 26.503 | Row-9*Row-10 |
| 13 | **Total Metal Sold (kg)** | 16.194 | 1.285 | Row-9*Row-11 |
| 14 | **$tCO_2e$ avoided (recycling)** | **0.045** | **0.033** | Wastebits $CO_2$ Equivalents Calculator |
| 15 | **Total $tCO_2e$ reduced (organic+recycling)** | **11.713** | **5.283** | Row-7+Row-14 |

By converting organic waste into valuable resources and improving recycling systems, the intervention contributed to methane emission reduction, lower environmental pollution, and reduced pressure on landfill and open dumping systems. BSF utilize their larvae to efficiently break down organic waste, converting it into nutrient-rich poultry and fish feed, and other valuable by-products (frass or organic fertilizer).

This method not only aids in waste management but also contributes to nutrient recycling and su stainable agriculture. At the systems level, the project promoted community-based circular economy practices, strengthened local waste value chains, encouraged behavioural change in household waste management, and demonstrated the potential of integrated waste-to-resource models for climate change mitigation and sustainable urban environmental management.

# 5. Discussion

### 5.1 The Primacy of Physical Infrastructure in Urban Settings

The central finding of our study is the significant behavioural shift toward proper waste segregation and communal bin usage when physical infrastructure is provided. We have observed a significant 31 percentage point increase in treatment households disposing of wet and dry waste in separate big drums, and a significant 24.1 percentage point increase in the daily disposal in these communal bins.

These results are highly consistent with emerging literature suggesting that reducing the "physical friction" of waste disposal is the most effective policy lever in urban environments. For instance, Hosono & Aoyagi (2018) found that simply distributing designated recycling buckets increased the segregation rates. Similarly, Wadehra & Nie (2023) demonstrated that providing free dustbins to households caused segregation rates to jump to over 30% within days, while information-only campaigns and monitoring had a negligible impact. Our findings reinforce the theory that for an urban, professional population who may prioritize convenience over environmental ideology, the immediate accessibility of infrastructure is a necessary precondition for behavioural compliance.

Furthermore, the intervention yielded a 13.6 percentage point increase in households actively reusing recyclable waste. While other studies in similar municipal populations achieved high reuse compliance (86.7% to 95.3%) through intensive interventions involving eight dedicated health education sessions over two weeks (El Karout & Altuwaijri, 2012), our results demonstrate that providing accessible physical infrastructure can also successfully shift reuse behaviours without the need for resource-intensive training.

### 5.2 Economic Incentives and Recyclable Markets

Beyond segregation, our intervention successfully catalysed economic behaviour, yielding a 14.7 percentage point increase in households actively selling their recyclable waste to scrap buyers. This finding is particularly relevant in the context of developing urban centres, where informal waste-picking networks are robust but underutilized by middle-to-high-income households.

Our results are consistent with the observational data presented by Daful (2023), which noted that over 55% of urban households in similar emerging cities will engage with local "iron condemn" buyers if the recyclables are properly accumulated. This is further corroborated by recent observational literature by Haider et al. (2013) which highlights the sheer scale of the informal market, finding that over 65% of urban households sell recyclables to street-level waste collectors (hawkers) while another 25% hand them to domestic workers. The study also highlighted the difference in the selling behaviour among households of different income-levels. By providing the small bins to easily separate these dry goods, our intervention successfully bridged the gap between household waste generation and the informal recycling market, proving that households will engage in circular economic behaviour if the storage constraints are removed.

### 5.3 Contextualizing the Null Results: Ceiling Effects and Intervention Duration

While infrastructures like small bins, large drums and leaflets drove segregation, the intervention did not significantly increase the frequency of daily waste or at-home composting. However, an analysis of the baseline context explains these null effects.

Regarding daily disposal, our study targeted an urban population with an established, albeit informal, daily disposal routine. At baseline, 71% of our control group was already disposing of waste daily. This high baseline created a ceiling effect; the urban professionals in our sample likely already had established routines for daily disposal (e.g., taking the trash out on the way to work), leaving little room for the intervention to create a statistically significant aggregate increase. Most households dispose of their waste directly from their kitchen windows or discard it into the local canal while commuting to work. Therefore, while other interventions observed significant increases in the frequency of households actively handing waste over to formal collectors following the installation of street bins system (Nepal et al., 2022b), our intervention primarily shifted how and where the waste was disposed (i.e., properly segregated into designated drums) rather than how often it was removed from the home.

Similarly, the null effect on household composting is likely a function of our study's short timeframe and the urban apartment context. While some studies have shown increases in composting when compost bins are placed directly outside apartment doors (DiGiacomo et al., 2018), composting is a complex, high-effort behaviour that requires sustained habit formation and space which is a huge limitation in urban flats. Unlike simply dropping a plastic bottle into a different bin, composting requires biological maintenance. Our findings suggest that short-term infrastructural interventions are sufficient to change low-effort behaviours, like segregation, but may require much longer durations (De Silva & Taylor, 2022) or sustained educational feedback (Dutta-Powell et al., 2023b) to shift high-effort behaviours like composting in an urban context.

### 5.4 Policy Implications

The findings of this study offer clear, actionable pathways for municipal authorities, urban planners, and environmental policymakers in emerging economies attempting to formalize municipal solid waste (MSW) management. By identifying exactly where behavioural bottlenecks occur among urban professionals, our results suggest targeted policy shifts regarding infrastructure provision, informal market integration, and organic waste processing.

A persistent challenge in municipal waste policy is determining the optimal allocation of resources between public awareness and physical capital. Our findings demonstrate that for an urban population with a high baseline rate of daily disposal (72.9%), providing designated physical infrastructure like small bins and large communal drums paired with basic instructional leaflets is highly effective. Specifically, the small bins yield a 31 percentage point increase in wet/dry segregation.

These results perfectly complement recent experimental evidence from Mymensingh, Bangladesh. The study demonstrated that while a control group receiving only collection services saw a mere 4% segregation rate, providing households with targeted informational brochures caused segregation to jump to 30%, and pairing that information with a physical dustbin pushed compliance even higher to 38% (Wadehra & Nie, 2023b). This suggests that untargeted mass-media awareness campaigns are likely inefficient. Instead, municipal budgets should mandate and subsidize the provision of localized physical infrastructure, such as colour-coded bins in apartment complexes, delivered simultaneously with targeted, household-level instructional materials. For urban professionals, eliminating the "transaction cost" of sourcing separate bins is the catalyst that turns environmental awareness into daily compliance.

Our intervention yielded a 14.7 percentage point increase in households actively selling their recyclable waste to scrap buyers, demonstrating a strong willingness among middle-to-high-income households to participate in the circular economy when storage constraints are removed. Currently, the macro-policy frameworks like Solid Management Rules 2021 emphasize formalized collection but lack the institutional capacity to implement Extended Producer Responsibility (EPR) mandates (Ministry of Environment, Forest and Climate Change (MoEFCC), 2021). Rather than City Corporations investing heavily in centralized, mechanized recycling fleets that compete with the informal sector, policy should focus on integration. Municipalities should formally register street-level hawkers, providing them with predictable ward-level access to apartment complexes. Furthermore, true EPR implementation should require fast-moving consumer goods (FMCG) and plastic manufacturers to subsidize the household-level sorting bins tested in our study. By shifting the financial burden of these bins to producers, municipalities can ensure a clean, sorted stream of dry recyclables flows directly into the highly efficient informal market.

The null effect observed regarding household composting provides a vital negative finding for urban planners. Composting is a space-intensive, high-effort biological process that requires sustained maintenance that are fundamentally incompatible with the spatial constraints of urban apartment flats. Municipal policies attempting to reduce landfill loads by promoting at-home composting in dense urban areas are likely to fail due to these structural limitations.

Instead, policy should pivot toward mid-scale, decentralized organic processing. With cleanly separated wet waste collected at the building level, municipalities can incentivize innovative biological treatments such as Black Soldier Fly (BSF) farming. Pilot initiatives in Bangladesh, such as the facilities operated by our implementation partner DYADIC in Cox's Bazar, process up to one ton of organic kitchen waste daily, utilizing BSF larvae to rapidly convert waste into high-protein poultry and aquaculture feed while mitigating landfill methane emissions (DYADIC Research Impacts, n.d.). City Corporations should provide land grants or tax incentives to private micro-enterprises to establish these BSF or biogas facilities at the neighbourhood or ward level, bridging the gap between household-level segregation and sustainable organic processing thus reducing the harmful methane gas emission from landfills.

**System level impact and projection**

Assuming the intervention achieves similar effectiveness at scale, the estimated annual carbon emission reduction for Cox's Bazar can be projected from the pilot findings. The pilot intervention reduced approximately 12.86 tCO2e annually. If scaled to the estimated 258,349 urban households in Cox's Bazar, and assuming 56.5% household participation in source sorting, approximately 145,967 households would participate in the intervention, and they would generate 34938.66 tons of waste (@1.36kh/day/hh) in six month (176 days). Converting this volume of waste into tonnes of carbon dioxide equivalent (tCO2e) using [$CO_2$ Equivalents Calculator], we find that the scaled intervention in urban areas of Cox's Bazar could potentially reduce nearly **21,837** tCO2e through improved source segregation, and Black Soldier Fly (BSF)-farming for producing protein rich poultry and aquatic feed. These findings demonstrate that Public-Private Partnerships in waste management systems can generate substantial climate mitigation benefits while simultaneously improving urban environmental management, and green job creation. The results have important policy implications for municipal solid waste management, climate adaptation, and low-carbon urban development in Bangladesh. First, they highlight the importance of integrating household-level source sorting into municipal waste management strategies to reduce methane emissions from unmanaged organic waste through anaerobic digestion. Second, the findings support investments in circular economy and waste-to-wealth enterprises such as composting, recycling, and BSF farming (for producing nutrition rich poultry and fish feed) as scalable climate-smart urban solutions. Third, the intervention demonstrates the potential for creating green jobs and youth-led enterprises within urban waste value chains, aligning with Bangladesh's climate commitments and renewable energy transition goals (MPEMR, 2025). Scaling such interventions through policy support, public-private partnerships, municipal financing, and community engagement could contribute significantly to national greenhouse gas reduction targets while strengthening sustainable and climate-resilient urban waste management systems.

**Implementation Challenges**

Scaling these recommendations will not be straightforward. Budget constraints in most Bangladesh municipalities make sustained bin distribution and collection difficult without donor support or clear cost-recovery plans. Sustaining public-private partnerships beyond a pilot phase also requires ongoing coordination between local government, waste collectors, and recycling markets, and these relationships can break down when financial incentives shift. On the behavioural side, six months may not be long enough to make sorting a permanent habit, and without reliable collection services households are likely to fall back on mixed disposal. BSF bioconversion systems also need trained operators and supply chains that are not yet in place across most municipalities. Addressing these challenges will require phased scale-up, targeted capacity-building, and the inclusion of waste management targets in city-level climate plans. Since findings come from a single city, replication studies across different urban contexts in Bangladesh would strengthen the case for national policy adoption.

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