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Pankaj Gupta, Priyanka Verma and Sunil Jaswal

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Systems Engineering Analysis of Municipal Solid Waste Collection, Segregation, and Processing Infrastructure in a Small Himalayan Town: A Case Study of Bilaspur Municipal Corporation, India

Pankaj Gupta[1], Priyanka Verma[1] and Sunil Jaswal[1]

[1] Department of Environmental Science, Himachal Pradesh University, Shimla-171005, India

†Corresponding author: Pankaj Gupta; pankajgupta08091975@gmail.com

ABSTRACT

Background: Designing an efficient solid waste management (SWM) system in small hill towns requires a proper technical evaluation due to terrain-related constraints and limited infrastructure capacity. **Method:** This paper, based on a study conducted in the Bilaspur Municipal Corporation (BMC), Himachal Pradesh, develops a systems-based diagnostic framework that integrates material flow analysis, collection efficiency assessment, infrastructure gap evaluation, and terrain-based analysis. The framework was applied to BMC, comprising 3,226 households (Census 2011 population: 13,654) and a projected 2024 population of approximately 15,500, with elevations ranging from 650 to 1,100 m and slope gradients between 5 and 25 per cent. A structured household survey covered 220 respondents across eleven wards (20 households per ward). **Results:** Using a per capita waste generation rate of 0.413 kg/day, total municipal waste generation was estimated at 6.4 Tonnes Per Day (TPD), of which organic waste accounted for over 65 per cent (≈4.2 TPD) and recyclables approximately 1.5 TPD. Source Segregation Efficiency (98.6 per cent) significantly exceeded the national urban average (30–40 per cent), reducing potential manual sorting requirements by 60–70 per cent. Collection Coverage Rate was 82.7 per cent, while the System Leakage Rate was 17.3 per cent (≈1.1 TPD), mainly in the wards with slopes >20% and road widths <3 m. The Infrastructure Adequacy Index was critically low (0.04). Based on respondent observations, disposal sites showed signs of leachate (reported by 100 per cent), vector presence (99.5 per cent), odour (99.1 per cent), and fire incidents (88.2 per cent); these are perceptual indicators, not direct field measurements. The 1.0–1.5 TPD vertical baling-to-co-processing model, which achieves 70–75 per cent volume reduction, further demonstrates viable downstream integration. **Conclusion:** Suggested interventions include a 4.2 TPD windrow composting facility (1,500–2,000 m²; 45–60 days retention), a 1.5 TPD manual MRF (200–300 m²), a 0.7 TPD engineered landfill (0.5 ha; 10-year life), 3–4 micro-transfer stations, optimized fleet deployment, RFID/GPS integration, and a 25–50 kg/day pharmaceutical incineration linkage.

Keywords: Systems Engineering Analysis, Municipal Solid Waste, Bilaspur Municipal Corporation, Material Flow Analysis, Collection System Performance Metrics, Infrastructure Gap Assessment, Terrain Constraint Analysis

1. INTRODUCTION

Management of Municipal Solid Waste (MSW) is one of the most important environmental governance challenges confronting urban India in the twenty-first century. The rapid urbanisation, shifting consumption patterns, and increasing per capita incomes have induced exponential growth in waste generation across urban areas (Joshi and Ahmed, 2016; Kumar et al., 2017). According to the Central Pollution Control Board (2021), approximately 160,038.9 metric tonnes of solid waste are generated per day in India, with urban areas contributing to the majority of the ecological burden. While extensive scholarly attention has been devoted to metropolitan waste management challenges, small and medium towns, those in the hilly regions, remain under-researched despite unique and challenging geo-climatic and infrastructural constraints (Marshall and Farahbakhsh, 2013; Ferronato and Torretta, 2019). Limited availability of land for developing a proper waste treatment facility in the hill towns includes steep topography, complicating collection logistics, seasonal population fluctuations, and severely constrained access to appropriate disposal sites (Datta, 2019; Sharma et al., 2022).

The household level is a critical initial point in the management of MSW. Decisions taken at the household level regarding waste storage, segregation, and disposal directly influence the performance and efficiency of downstream collection, transportation, and processing systems. Therefore, a clear understanding of household practices and the factors influencing them is important for designing effective municipal-level interventions. However, the existing research on waste management in the hill towns has largely emphasised socio-behavioural and environmental aspects. In contrast, assessing the engineering efficiency of collection systems, infrastructure capability, material flow dynamics, and terrain-sensitive system design remains limited (Tchobanoglous et al., 2002; Brunner and Rechberger, 2016). Thus, there is an urgent need to develop engineering-oriented analytical frameworks that can convert household-level survey findings into practical and measurable design parameters for developing the waste management infrastructure in the hilly regions (Ghiani et al., 2014; Hannan et al., 2012).

While engineering tools such as material flow analysis (MFA), collection performance modelling, and infrastructure gap assessment have been successfully implemented in plain areas, these methods can be adapted carefully to suit the distinct geo-climatic conditions, settlement patterns and demographic characteristics of hilly terrain. This paper uses a systems engineering framework to evaluate household solid waste management in BMC, by addressing three objectives: (1) to quantify household waste generation rates and composition as engineering design parameters for sizing processing facilities effectively, planning vehicle capacity, and selecting processing technology; (2) to evaluate collection system efficiency, infrastructure use, and the collection-processing gap using material flow analysis and engineering performance metrics; and (3) to develop engineering design specifications for terrain-sensitive waste management infrastructure including processing facilities, micro-transfer stations, and optimised collection systems for hill towns. In doing so, this study directly supports the achievement of Sustainable Development Goal (SDG) 11 (Sustainable Cities and Communities), by strengthening municipal solid waste infrastructure in an under-served hill town, and SDG 12 (Responsible Consumption and Production), through improved source segregation, material recovery, and reduced landfill dependency.

The novelty of this study lies in four interconnected contributions that make it distinct from earlier research on solid waste management in hill towns. Firstly, earlier studies were mostly focused either on socio-behavioural aspects, such as household attitudes, willingness to pay, and public participation, or on ecological impacts like landfill leachate and open-dump contamination. In contrast, this study combines behavioural survey data with engineering performance indicators within a single systems-based framework, an approach that remains largely unmapped in the context of hill-town municipal solid waste management. Secondly, the study applies material flow analysis (MFA) to a small Himalayan municipality, addressing an important methodological gap. Although MFA has been widely used in metropolitan and peri-urban areas, it has rarely been applied to small hill towns with populations below 20,000 and steep terrain conditions exceeding 20 per cent gradient.

Thirdly, the terrain-based classification system (Categories A, B, and C), along with its connection to infrastructure planning, introduces a terrain-sensitive design approach that has not been developed formally in Indian municipal waste-management literature. The framework differentiates requirements for micro-transfer stations, vehicle types, and waste-collection frequency according to slope conditions and road accessibility. Fourthly, the Infrastructure Adequacy Index (IAI), developed using a frequency-weighted combination of respondent-reported environmental indicators, serves as a quantitative measure of infrastructure performance and failure. This allows comparisons across municipalities with similar geo-climatic conditions. Together, these contributions provide a practical and replicable analytical framework that translates household-level survey findings into engineering-oriented infrastructure specifications, including waste quantities, spatial requirements, and vehicle-capacity estimates, especially suited for small hill municipalities.

2. MATERIALS AND METHODS

2.1 Study Area

Bilaspur Municipal Corporation is located in the mid-Himalayan region of Himachal Pradesh, India (31.3260°N, 76.7620°E), at an altitude ranging from 650 to 1,100 metres above mean sea level. The town is the administrative headquarters of Bilaspur district and comprises eleven municipal wards. The municipality exhibits characteristics typical of small hill settlements, including mixed residential-commercial land-use patterns and a traditional reliance on nearby valleys for natural drainage. According to Census 2011 data, BMC had approximately 3,226 households and a population of 13,654; applying a decadal growth rate of 12.08 per cent, the population is projected to reach approximately 15,500 by 2024 (Census of India, 2011). The terrain has gradients ranging from 5 per cent in the central commercial zone to over 25 per cent in peripheral wards, with road widths varying from less than 3 metres in older residential areas to 7-10 metres along arterial routes, creating significant engineering constraints for the conventional waste collection vehicles.

2.2 Survey Design and Data Collection

Primary data were collected between November 2024 and June 2025 through a self-developed structured questionnaire covering 220 households, with equal representation (n=20) from each of the eleven municipal wards. The questionnaire captured data on diverse facets, like socio-economic characteristics, types of waste generated, storage methods, segregation practices, disposal frequency and channels, awareness regarding SWM, perceptions about service quality, and environmental observations around the waste disposal sites.

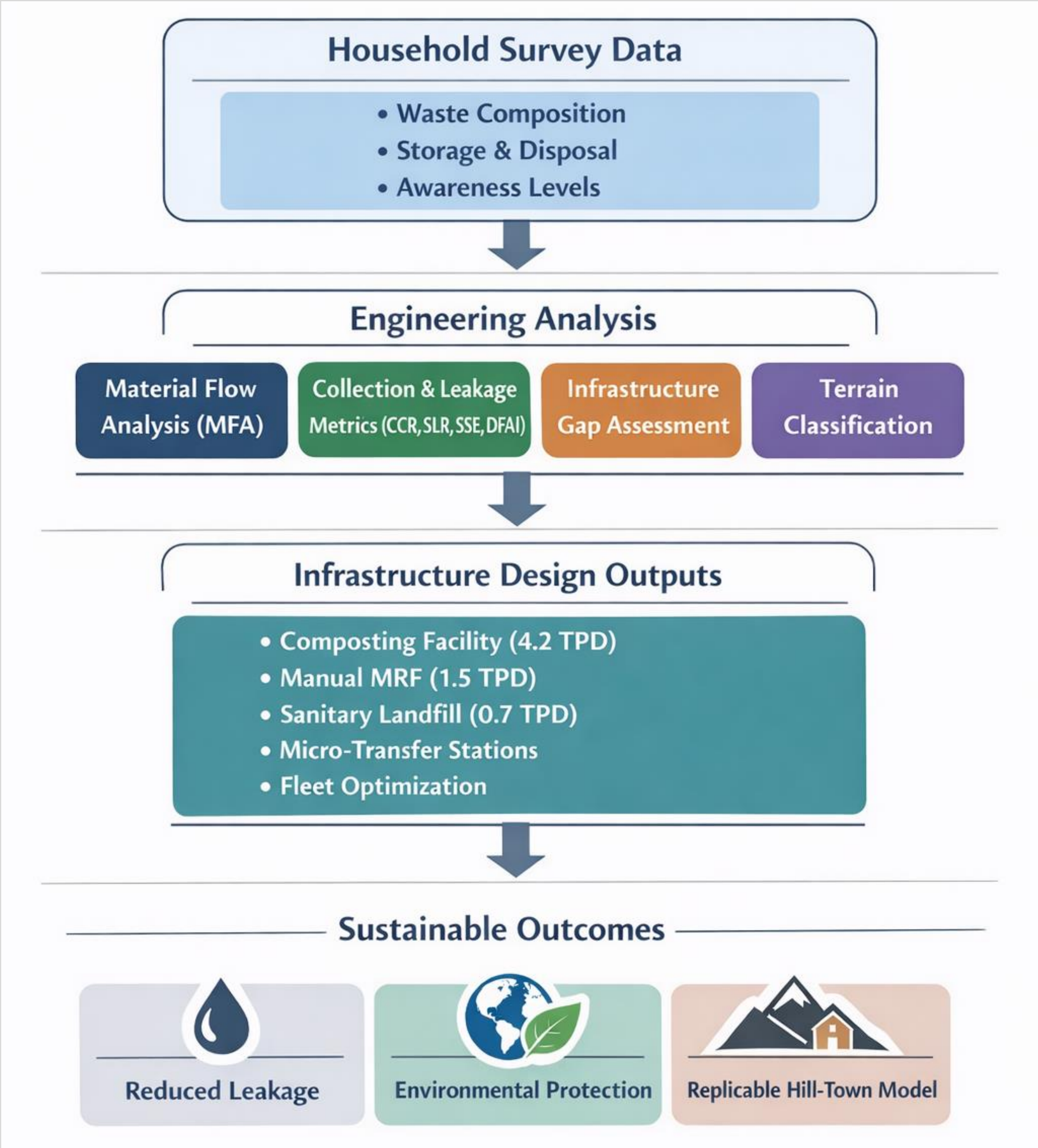


Figure 1: Integrated Systems Engineering Framework for Terrain-Sensitive Waste Management Planning

2.3 Statistical and Engineering Analysis

The collected data were analysed using descriptive statistics and frequency distribution methods to understand patterns of household waste generation, storage, segregation, and disposal practices. Statistical analysis was carried out using SPSS version 23.

2.4 Material Flow Analysis (MFA)

A material flow analysis framework was employed to quantify waste flows across the entire management chain from household generation through storage, collection, transport, and final disposal (Brunner and Rechberger, 2016). The system boundary included all eleven wards of BMC. To ensure analytical clarity, the study uses data from three distinct sources, which are clearly differentiated throughout the paper. First, directly measured survey data include frequencies, proportions, and categorical responses collected from the 220 surveyed households, such as waste segregation practices, disposal methods, and disposal frequency. Second, secondary estimates of waste quantities were generated by applying published per capita waste-generation rates and waste-composition benchmarks to the projected population of BMC. These estimates include values such as the total daily waste generation of 6.4 tonnes per day (TPD) and an organic waste fraction of approximately 65 per cent. Third, extrapolated engineering design values and infrastructure specifications were calculated from these estimates to support infrastructure planning, including projections for a 4.2 TPD composting facility and a landfill requirement of approximately 0.5 hectares. It is important to note that none of the waste-quantity or composition figures reported in this study -- the total generation estimate, organic fraction, recyclable fraction, or inert fraction -- were derived from gravimetric sampling or physical waste characterisation; they are secondary estimates obtained by applying published per-capita generation rates and composition benchmarks to the survey-derived population data, and should be treated as planning-level estimates rather than measured results. Waste generation rates were assessed using the Himachal Pradesh per capita generation rate of 0.413 kg/day (TERI, 2015) applied to the estimated 2024 population of 15,500, yielding a total estimated municipal waste generation of approximately 6.4 tonnes per day (TPD). Although Census 2011 reported a population of 13,654, all engineering calculations in this study are based on the projected 2024 population of approximately 15,500, derived using a decadal growth rate of 12.08 per cent. This projection ensures that infrastructure sizing reflects current service demand rather than historical demographic data. Mass balance calculations were done at each stage of the waste management chain to quantify material flows across formal collection systems, informal disposal routes (such as valley dumping and kitchen garden disposal), and overall system leakage.

The organic fraction of waste (~65%, approximately 4.2 TPD) was not measured directly. Instead, it was estimated by combining survey findings, which showed that most households generated food and vegetable waste, with published waste-composition benchmarks for small Indian towns (CPCB, 2021). Similarly, the recyclable fraction (~23%, approximately 1.5 TPD), including plastics, paper and cardboard, glass, and metal tins, was estimated using survey-based composition data. The remaining inert fraction (~12%, approximately 0.7 TPD) was calculated through mass balance by subtracting the organic and recyclable portions from the total estimated waste generation. These estimated waste fractions were subsequently used as engineering inputs for planning and sizing waste-management facilities.

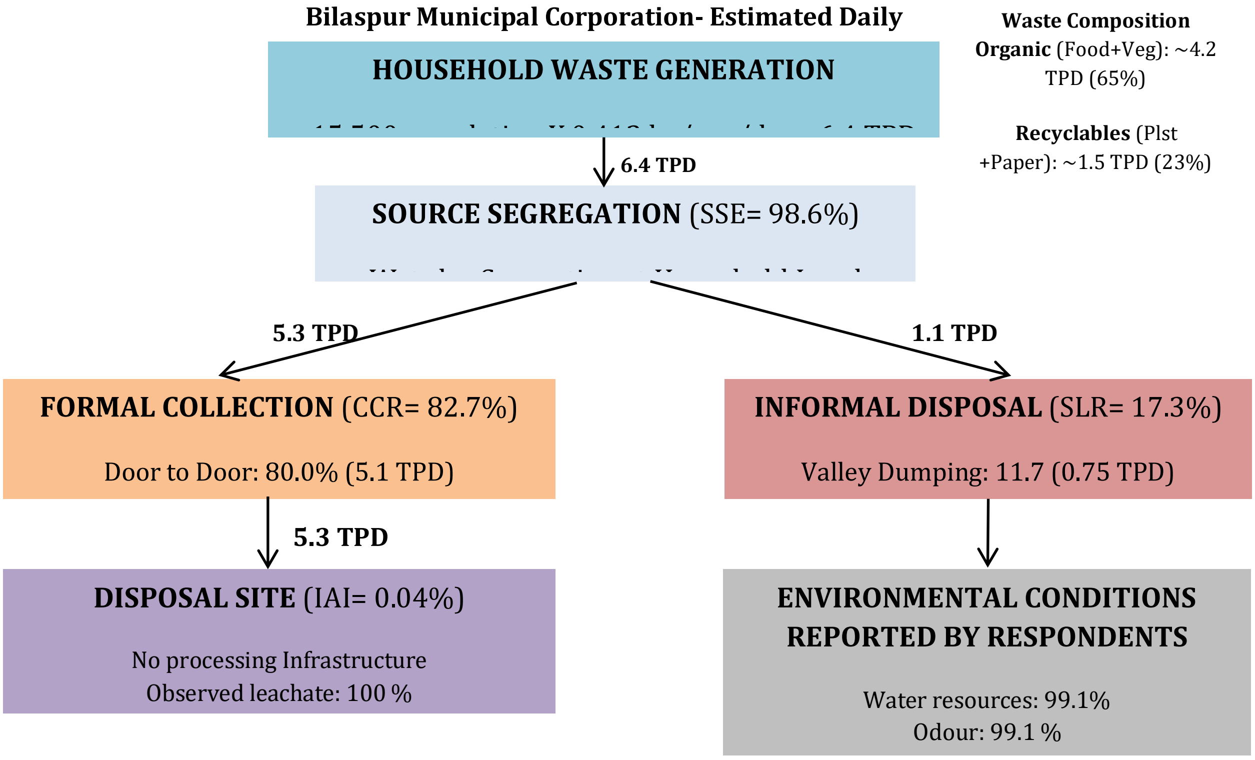


Figure 2: Material Flow Analysis (MFA) of Municipal Solid Waste Management Chain

2.5 Collection System Performance Metrics

Engineering performance indicators were calculated from survey data to assess the efficiency of the collection system. The following metrics were calculated:

- Collection Coverage Rate (CCR) = (households served by formal collection channels / total surveyed households) x 100
- System Leakage Rate (SLR) = (households using informal disposal / total surveyed households) x 100
- Disposal Frequency Adequacy Index (DFAI), categorising daily disposal as optimal (score 3), alternate-day as adequate (score 2), and less frequent as sub-optimal (score 1), with a weighted mean score computed across all households; and
- Source Segregation Efficiency (SSE) = (households practising wet-dry segregation / total households) x 100, interpreted as a measure of input quality for downstream processing facilities.

2.6 Infrastructure Gap Assessment

An infrastructure gap assessment model was developed to quantify the shortage between required and installed waste processing capacity. The required capacity for each infrastructure component was computed from the MFA outputs: Composting facility capacity (based on organic waste fraction x total generation rate), MRF capacity (based on recyclable fraction x total generation rate), and Sanitary landfill capacity (for residual inert waste). These were compared against existing installed capacity to derive gap ratios.

An Infrastructure Adequacy Index (IAI) was developed to measure the extent of infrastructure failure at the disposal site based on environmental conditions reported by survey respondents. The index was calculated in two stages. In the first stage, a binary approach was used, expressed as:

$$IAI\_binary = 1 - (C / n)$$

Where C represents the number of indicators with observation rates of 95 per cent or higher, and n represents the total number of indicators assessed (n = 8 in this study)

In the second stage, a frequency-weighted version of the index was calculated using the formula:

$$IAI\_weighted = 1 - (1/n) \times \Sigma p_i$$

Where p_i refers to the proportion of respondents reporting a particular environmental indicator

Unlike the binary approach, this weighted formulation captures the intensity and frequency of observed conditions rather than treating all indicators equally. The index ranges from 0 to 1. A value close to 0 indicates critical infrastructure failure, where nearly all respondents report the presence of environmental problems, while a value close to 1 reflects relatively adequate infrastructure conditions with minimal reported issues. Therefore, lower IAI values signify greater failure of downstream waste-management infrastructure. It is important to note that the IAI is constructed entirely from respondent-reported perceptions of leachate, vector presence, odour, and fire incidents at disposal sites, rather than from site inspection, water-quality testing, or a formal landfill engineering assessment. It should therefore be interpreted as a perception-based indicator of community-perceived infrastructure concern, not as a validated technical adequacy metric.

2.7 Terrain Constraint Analysis

Terrain constraints on collection system design were analysed by comparing informal disposal rates (particularly valley dumping) with ward-level availability features. Wards were classified into three terrain accessibility categories: Category A (accessible: gradient <10%, road width >5 m, suitable for standard collection vehicles); Category B (partially accessible: gradient 10–20%, road width 3–5 m, requiring small-format collection vehicles); and Category C (terrain-constrained: gradient >20%, road width <3 m, requiring micro-collection solutions or manual porterage). This classification is presented as a conceptual framework linking terrain conditions to collection-vehicle requirements; it was not disaggregated to a ward-wise table (showing slope, road width, collection coverage, leakage rate, and proposed intervention by ward) in the present analysis. Such a ward-level breakdown, which would allow direct validation of the classification against observed performance, is identified as a priority for future work.

3. RESULTS

3.1 Socio-Demographic Profile

The socio-demographic profile of respondents is presented in Table 1.

Table 1: Socio-Demographic Profile of Survey Respondents (N=220)

Variable	Category	N	per cent
Age Group	Below 20 years	6	2.7
	21-40 years	89	40.5
	41-60 years	84	38.2
	61+ years	41	18.6
Gender	Male	120	54.5
	Female	100	45.5
Education	Illiterate	14	6.4
	Below Matriculation	80	36.4
	Plus-Two	55	25.0
	Graduation+	71	32.3
Income (Rs.)	Below 50,000	52	23.6
	50,000-1,00,000	103	46.8
	Above 1,00,000	65	29.6

The 220 survey respondents were mainly from the economically active age group (21–60 years: 78.6 per cent); a further 18.6 per cent were aged 61 and above, and a small proportion (2.7 per cent) were below 20 years, with balanced gender representation (54.5 per cent male, 45.5 per cent female). Educational attainment showed that 6.4 per cent of respondents were illiterate, 36.4 per cent had below-matriculation education, 25.0 per cent completed plus-two level, and 32.3 per cent were graduates. Nearly half of the respondents (46.8 per cent) earned Rs. 50,000–1,00,000 annually. Notably, 78.6 per cent had been residing in BMC for over 20 years.

3.2 Waste Generation and Composition

Table 2 shows that plastics and food waste were generated by all surveyed households. Paper and carton waste were reported by 94.5 per cent of households, while vegetable waste was reported by 93.2 per cent. A significant concern was pharmaceutical waste. Nearly 67.7 per cent of households reported medicine-related waste. No household clearly reported generating e-waste. Using the Himachal Pradesh per capita waste generation rate of 0.413 kg/day (TERI, 2015) and a population of 15,500, total daily waste generation is estimated at 6.4 TPD.

Table 2: Types of Waste Generated by Households (N=220)

Waste Type	N	per cent	Level
Plastics	220	100.0	Universal
Food Waste	220	100.0	Universal
Paper/Carton	208	94.5	Very High
Vegetable Waste	205	93.2	Very High
Medicines	149	67.7	Hazardous
Farm Waste	17	7.7	Low
Glass/Tins	11	5.0	Very Low

The organic fraction of waste was estimated rather than directly measured. This estimate was based on two sources of evidence. First, survey findings showed that almost all households generated food waste (100 per cent) and vegetable waste (93.2 per cent), indicating that biodegradable materials form the dominant component of household waste. Second, published waste-composition benchmarks for small Indian hill towns report that the organic fraction generally ranges between 60 and 70 per cent by weight (CPCB, 2021; TERI, 2015). Using the midpoint value of 65 per cent and applying it to the estimated total waste generation of 6.4 TPD resulted in an estimated organic fraction of approximately 4.2 TPD. This value should be understood as a planning and design estimate rather than a direct gravimetric measurement. Therefore, a detailed waste-characterisation study is recommended before undertaking final facility design and implementation.

The

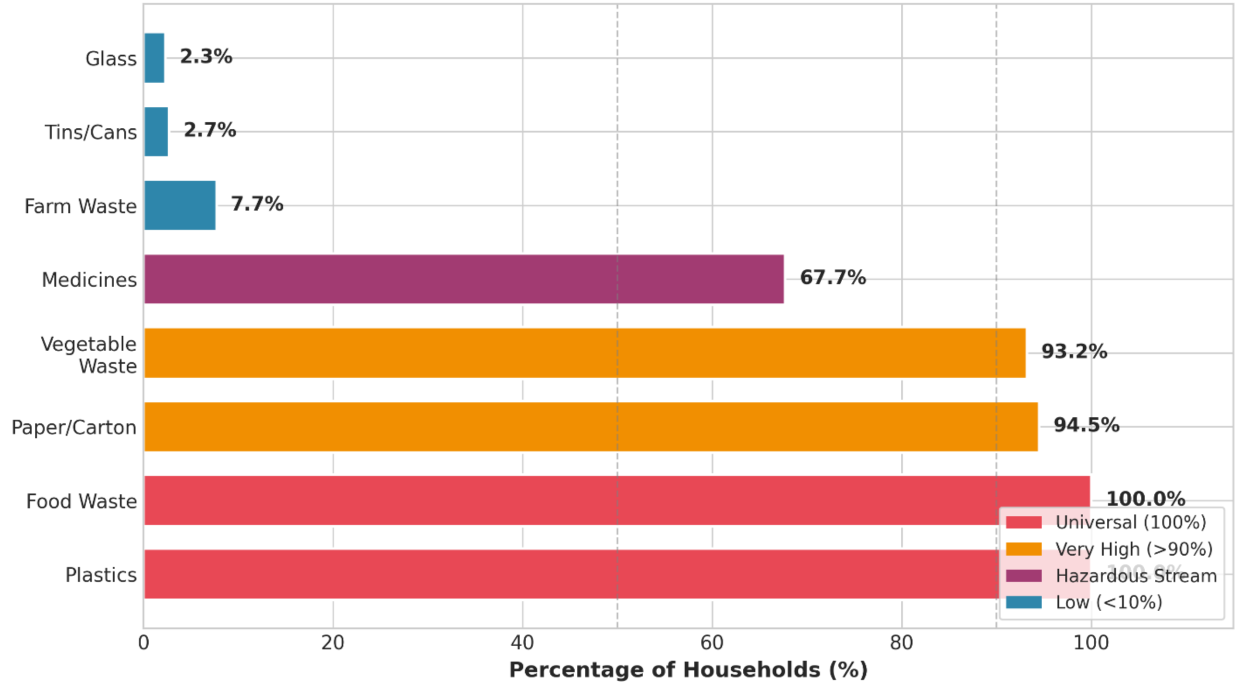


Figure 3: Types of Wastes Generated by the Households (N=220)

recyclable dry waste fraction is estimated at approximately 1.5 TPD and determines the required processing capacity of the proposed MRF. In addition, pharmaceutical waste represents a distinct hazardous stream. It was reported by 67.7 per cent of the 220 surveyed households (n = 149), equivalent to an estimated 2,183 of the 3,226 total BMC households, and thus requires a dedicated handling system. Based on reported pharmaceutical waste generation rates of 10–15 grams per household per week (Mahesh et al., 2020), the projected daily capacity requirement ranges between 15 and 25 kilograms.

3.3 Storage and Segregation Practices

A total of 74.1 per cent of respondents reported using proper dustbins for household waste storage. A remarkably high 98.6 per cent of households stated that they separate wet and dry waste. This figure significantly exceeds the national urban average of 30–40 per cent (Kumar and Samadder, 2017), indicating that BMC's door-to-door collection system has effectively institutionalised segregation as a regular household practice. Pre-segregated recyclable waste substantially reduces the need for mechanical segregation — potentially by 60–70 per cent compared to systems handling mixed waste. However, 25.9 per cent of households did not use appropriate dustbins (57 out of 220 surveyed households), indicating a notable gap in storage infrastructure.

3.4 Disposal Methods and Frequency

A total of 80.0 per cent of households rely on door-to-door collection vans (Table 3). Around 11.7 per cent dispose of waste in valleys or *khads* (water streams). The Collection Coverage Rate (CCR) is 82.7 per cent. CCR = Households served by formal collection / Total surveyed households × 100 = 182/220 × 100 = 82.7%. The formal system handles approximately 5.3 TPD out of the total 6.4 TPD of generated waste. The System Leakage Rate (SLR) stands at 17.3 per cent (SLR = 38/220 × 100 = 17.3%), with valley dumping alone contributing around 0.75 TPD. The Disposal Frequency Adequacy Index (DFAI) was computed as a weighted mean (daily = 3, alternate-day = 2, every three days = 1, less frequent = 0), yielding a value of 2.03, suggesting disposal frequency is generally satisfactory but not yet optimal.

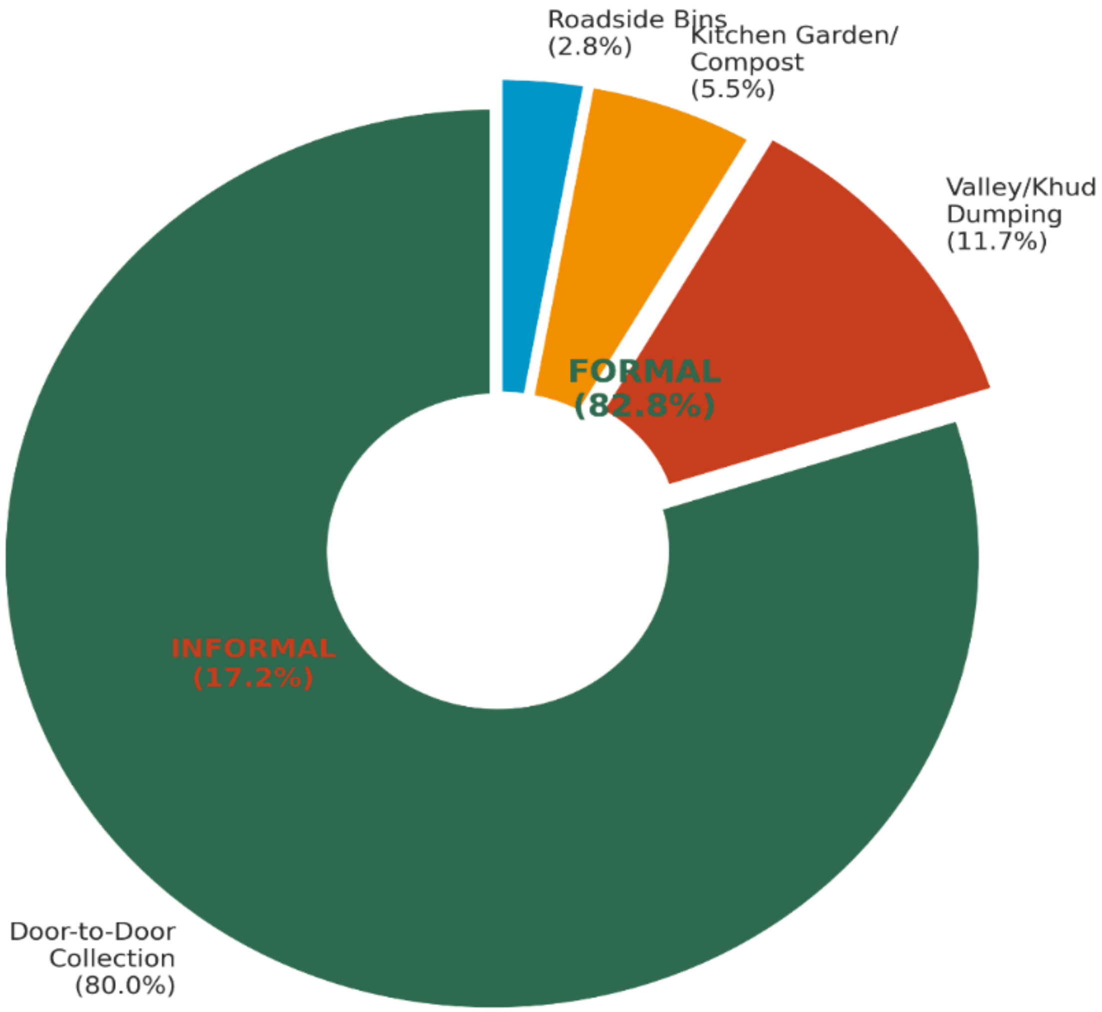
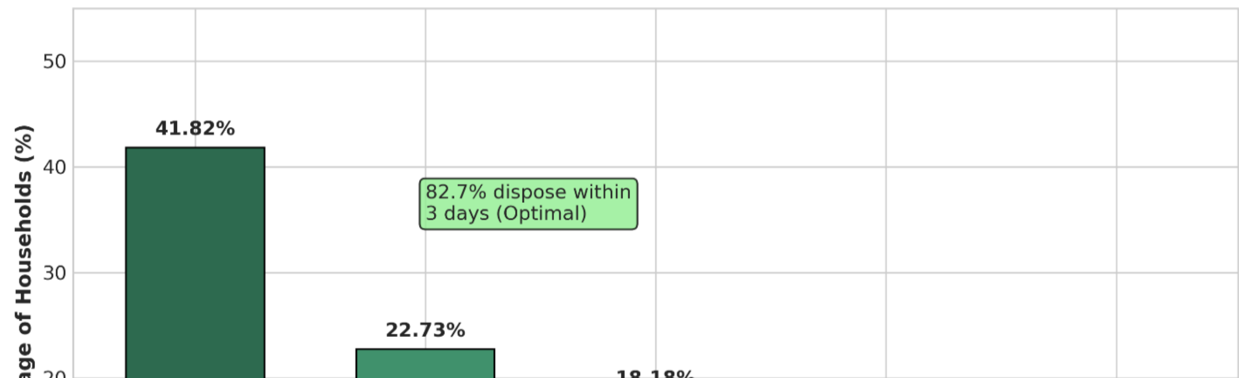


Figure 4: Household Waste Disposal Methods (N=220)

Table 3: Waste Disposal Methods (N=220)

Disposal Location	N (per cent)	Classification
Door-to-Door Van	176 (80.0 per cent)	Formal
Valley/Khad	26 (11.7 per cent)	Informal
Kitchen Garden	12 (5.5 per cent)	Informal
Roadside Bins	6 (2.8 per cent)	Formal



3.5 Awareness Assessment

Awareness of SWM facilities was reported by 66.8 per cent of respondents; broader theoretical SWM awareness was comparatively lower at 46.8 per cent (Table 5). Awareness of environmental impacts was nearly universal at 98.2 per cent, and health impact awareness was 99.5 per cent. Figure 6 presents the Multi-Dimensional Awareness Profile. Television was the main information source for 42.8 per cent, followed by digital media at 25.3 per cent.

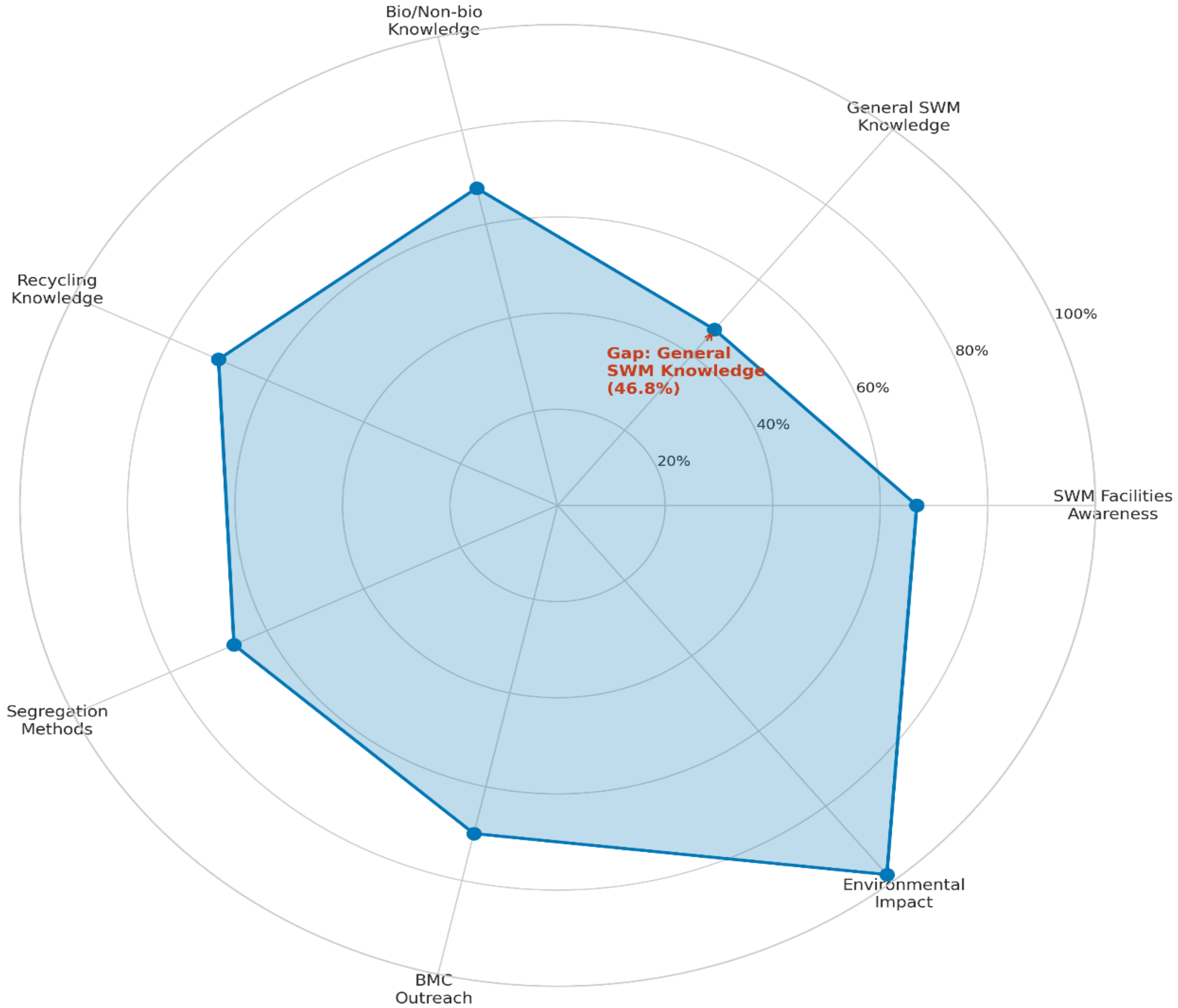


Figure 6: Multi-Dimensional Awareness Profile (Radar Chart)

Table 5: Multi-Dimensional Awareness Assessment (N=220)

Awareness Indicator	Yes (per cent)	Level
Aware of SWM Facilities	66.8	Moderate
General SWM Awareness	46.8	Low
Bio/Non-biodegradable Knowledge	67.7	Moderate

Recycling Knowledge	70.0	High
Made Aware by BMC	70.0	High
Campaign Attendance	5.9	Very Low
Environmental Impact Awareness	98.2	Very High
Health Impact Awareness	99.5	Very High

Source: Primary Survey, 2024-25. Note: Very High (>90 per cent), High (70-90 per cent), Moderate (50-70 per cent), Low (<50 per cent)

3.6 Environmental Observations

Although a majority of households expressed satisfaction with waste-collection services, respondents also reported observing several serious environmental problems around disposal sites. All respondents stated that they had seen dark or coloured water flowing near waste dumps, which may indicate the presence of leachate, although this was not confirmed through laboratory testing. Other commonly reported conditions included the presence of vectors and domestic animals near dumping areas (99.5 per cent), foul odour and rodents (99.1 per cent each), fire incidents at dumping sites (88.2 per cent), scattered waste in public spaces (97.3 per cent), and the apparent movement of waste into nearby water bodies (99.1 per cent). It is important to clarify that these findings are based on respondent perceptions collected through a structured household survey and should not be interpreted as direct environmental or laboratory measurements of contamination. However, the consistently high frequency of these observations across respondents provides strong indirect evidence of deficiencies in waste-management infrastructure. For this reason, these observations were interpreted as qualitative indicators of infrastructure adequacy rather than as quantified measures of environmental pollution.

Eight such indicators were evaluated. Seven exhibited observation rates exceeding 95 per cent. Using the binary formulation (Step 1), $IAI\_binary = 1 - (7/8) = 0.125$.

In the second step, a frequency-weighted adjustment was applied using the formula: $IAI\_weighted = 1 - (1/8) \times \Sigma p_i$.

The eight environmental indicators and their observed proportions were as follows: leachate presence (1.000), vector presence (0.995), domestic animals near dumping areas (0.995), foul odour (0.991), rodent presence (0.991), waste entering nearby water bodies (0.991), scattered waste in public areas (0.973), and fire incidents (0.882). The average prevalence of these indicators, obtained by summing the values and dividing by eight, was 0.960. Accordingly, the weighted Infrastructure Adequacy Index (IAI) was calculated as:

$IAI\_weighted = 1 - 0.960 = 0.04$.

This very low index value indicates severe inadequacy in downstream waste-management infrastructure. In particular, the observation by 99.1 per cent of respondents that waste was entering nearby water bodies points towards insufficient surface-water diversion and containment measures at disposal sites. However, direct water-quality testing would be necessary to scientifically confirm contamination levels. Figure 7 presents the environmental observations reported by respondents at waste sites.

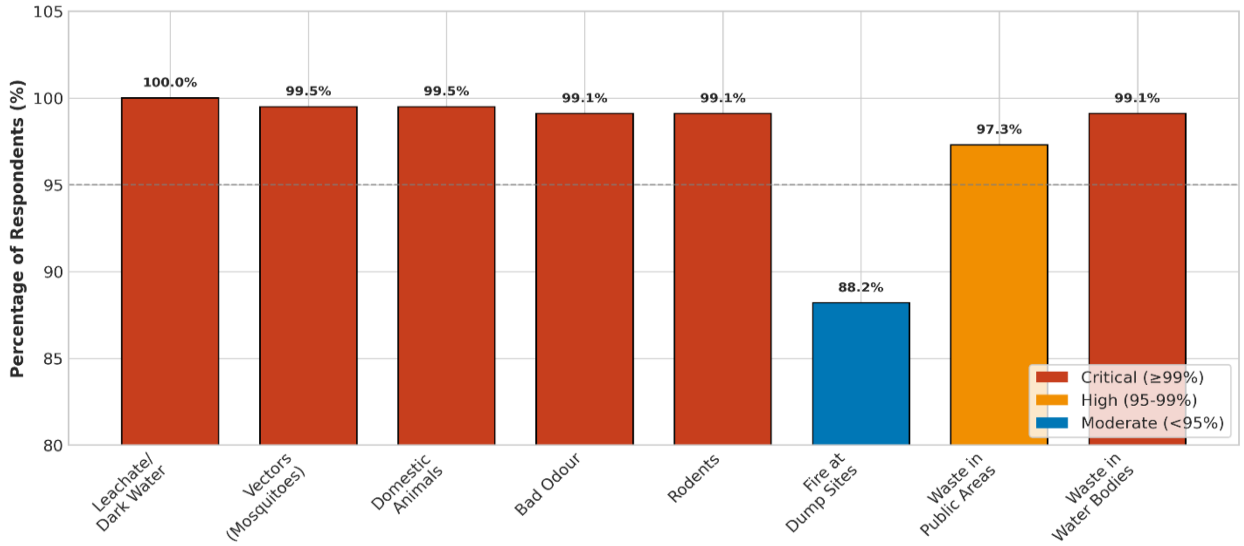


Figure 7: Environmental Observations around Waste Sites (N=220)

Table 6: Infrastructure Gap Analysis

Facility	Required Capacity	Existing	Gap
Composting	4.2 TPD	0	4.2 TPD
MRF	1.5 TPD	0	1.5 TPD
Landfill	0.7 TPD	Open dump	Full gap
Baling	1–1.5 TP	1–1.5 TP	Adequate

4. DISCUSSION

4.1 Waste Composition and Emerging Hazardous Streams

The waste composition profile observed in this study reflects patterns typical of small Indian towns undergoing economic transition. The universal generation of plastic and food waste aligns with findings from comparable urban centres across South Asia (Guerrero et al., 2013; Ferronato and Torretta, 2019). An important finding is that 67.7 per cent of the surveyed households (n = 149) reported medicine-related waste, indicating that pharmaceutical waste has emerged as a distinct hazardous stream within the BMC household waste mix. Most small Indian municipalities, including BMC, lack dedicated collection and treatment infrastructure for pharmaceutical waste. Inappropriate co-disposal with general waste or discharge into valleys can introduce bioactive compounds into groundwater and surface water systems, contributing to antimicrobial resistance and aquatic ecosystem disruption (Mahesh et al., 2020).

From a systems engineering perspective, the waste-composition data serve two important purposes. First, they indicate that biodegradable waste is the dominant component of the waste stream, estimated at approximately 65 per cent by weight. This estimate is based on benchmark-guided inference rather than direct gravimetric measurement and supports the selection of windrow composting as the most suitable primary treatment technology. Second, the data highlight pharmaceutical waste as a relatively small but potentially hazardous waste stream that requires a separate management system. Based on reported pharmaceutical waste generation rates of 10–15 g per household per week (Mahesh et al., 2020) and extrapolation to the estimated 2,183 affected households, the projected pharmaceutical waste quantity is approximately 15–25 kg per day. Although small in volume, this quantity is sufficient to justify a dedicated incineration unit with a capacity of 25–50 kg/day operating at temperatures above 850°C. Similarly, the estimated composting facility area of 1,500–2,000 m^2 was calculated using an estimated organic waste throughput of approximately 4.2 TPD along with standard windrow sizing criteria (Tchobanoglous et al., 2002). The design also assumes a retention period of 45–60 days, which is consistent with aerobic composting practices commonly used for food-waste streams of this scale.

4.2 Infrastructure-Driven Behaviour Change: The Door-to-Door Model

The 98.6 per cent source segregation rate in BMC substantially exceeds the national urban average of 30–40 per cent. This performance is closely linked to the door-to-door collection model, which removes distance and convenience barriers and creates regular temporal cues that act as behavioural triggers (Wood and Neal, 2007). Continuous interaction between households and collection workers creates a sense of social accountability. Evidence from Italy (Laurieri et al., 2020), Spain (Gallardo et al., 2012), Belgium (De Jaeger and Eyckmans, 2015), and several developing country contexts (Kassim and Ali, 2006; Hazra and Goel, 2009) demonstrates substantial improvements in source segregation after implementing door-to-door collection systems. These findings indicate that infrastructure design can operate as a behavioural policy instrument.

4.3 Valley Dumping: A Terrain-Specific Challenge

Despite strong overall system performance, valley dumping persists at 11.7 per cent, highlighting infrastructure-related constraints in steep terrain. Valleys (locally known as khads) have historically served as informal disposal routes, creating behavioural path dependency. Valley dumping in hill regions differs significantly from open dumping in plain areas: steep slopes act as natural transmission channels, and the rapid disappearance of visible accumulation at the dumping point weakens behavioural deterrence while the environmental penalties, contamination of springs and stream recharge zones, remain severe. Terrain-sensitive engineering interventions are proposed: micro-transfer stations (1–2 m^3 capacity) at Category C zone junctions; compact electric three-wheelers (500–800 kg payload) for Category B zones; and gabion retaining walls (1.2–1.5 m height) at identified dumping hotspots. These interventions are proposed at the level of the terrain-category framework rather than validated against ward-wise performance data (see Section 2.7).

4.4 The Collection-Processing Gap

A key finding of this study is the clear mismatch between the efficiency of waste collection and the poor condition of downstream waste treatment and disposal systems, referred to here as the “collection–processing gap.” Survey findings show that 82.7 per cent of households in BMC receive formal door-to-door waste collection services, while the source-segregation rate of 98.6 per cent is significantly higher than the national urban average (Table 4). These findings indicate that the primary waste-collection system is functioning relatively well.

Table 4: Engineering Performance Indicators

Indicator	Value	Engineering Implication
SSE	98.6%	Reduced MRF mechanisation
CCR	82.7%	5.3 TPD collected
SLR	17.3%	1.1 TPD leakage
DFAI	2.03	Near adequate
IAI	0.04	Perceived Critical Concern

However, the Infrastructure Adequacy Index (IAI) value of 0.04, along with the widespread reporting of adverse environmental conditions at the disposal site, suggests that downstream waste-processing and disposal infrastructure is unable to handle the quantity of waste being collected effectively. As this index is derived from respondent perceptions rather than site inspection or laboratory testing, it should be read as evidence of widespread perceived environmental distress rather than a validated technical assessment. Similar patterns, where collection efficiency is not supported by adequate treatment and disposal capacity, have been reported in municipal waste systems across many developing countries (Guerrero et al., 2013; Ferronato and Torretta, 2019). According to Tchobanoglous et al. (2002), this reflects a systems-level imbalance in which investments in waste collection infrastructure are not matched by equivalent investments in processing and disposal facilities (Tchobanoglous et al., 2002; Guerrero et al., 2013; MoEF and CC, 2016).

In the case of BMC, this imbalance is particularly severe. Although the collection system transfers approximately 5.3 TPD of waste to the disposal site, the site lacks essential infrastructure required under India’s Solid Waste Management Rules (2016), including engineered liner systems, leachate collection mechanisms, daily soil cover practices, and landfill gas-management systems. As a result, effective waste collection alone does not solve the waste problem; instead, it shifts and concentrates the environmental burden at the disposal site.

This pattern reflects a broader weakness in waste management systems across developing countries. Collection systems are simpler to implement and require lower capital investment. In contrast, waste processing and disposal demand detailed engineering design, skilled personnel, environmental protection measures, and continuous monitoring. Consequently, waste is transported efficiently from households to poorly managed dump sites, shifting and concentrating the environmental burden. BMC has taken initial steps to address this gap through the vertical baling machine (operational since 2024), which processes 1.0–1.5 TPD of non-recyclable dry waste and diverts approximately 470 tonnes annually from uncontrolled dumping.

4.5 Collection System Optimisation Potential

The current waste disposal pattern shows a substantial scope for improvement. Universal daily collection may not be the most efficient approach in low-density wards. An improved framework should adopt differentiated collection frequencies based on settlement density. GIS-based route planning and GPS-enabled fleet management can reduce fleet operating costs by 15–25 per cent (Ghiani et al., 2014).

4.6 Baling Facility, Infrastructure Sizing, and Technology Framework

A vertical baling machine (J.K. Machine Tools, Gujarat Pvt. Ltd.) has been operational at BMC since 2024, processing 1.0–1.5 TPD of non-recyclable dry waste. The baling process achieves a 70–75 per cent volume reduction and has reduced transport frequency from 5–8 to 2–3 trips per week, yielding estimated annual transport cost savings of Rs. 3.12–7.80 lakhs. Baled waste is co-processed at UltraTech Cement (Darlaghat) and ACC Gagal Cement Works (Barmana) at temperatures of 1,400–1,600°C. Complementary infrastructure required includes: a 4.2 TPD aerobic windrow composting facility (1,500–2,000 m^2), a 1.5 TPD manual MRF, an engineered landfill for approximately 0.7 TPD residual waste (0.5 ha, 10-year life), and a pharmaceutical incineration unit at 25–50 kg/day. Smart technologies including RFID-tagged bins, ultrasonic fill-level sensors, and GPS fleet management hold potential for further operational improvement (Pardini et al., 2019). The capacities proposed above (composting, MRF, landfill, and pharmaceutical incineration) are first-order sizing estimates derived from secondary generation and composition rates rather than final design specifications; they are intended to guide preliminary planning and land allocation, and should be confirmed through site-specific geotechnical assessment, gravimetric waste-composition verification, and cost-benefit analysis before capital investment.

5. KEY FINDINGS

Five key findings emerge from the analysis. First, plastic and food waste are generated by all households, and pharmaceutical waste has emerged as a distinct hazardous stream. Total estimated waste generation is 6.4 TPD, of which nearly 65 per cent is organic, indicating a potential need for composting capacity of comparable scale, pending confirmation by direct waste characterisation. Second, source segregation efficiency is exceptionally high, largely due to the regular door-to-door collection system. Third, formal collection covers 82.7 per cent of households, with 17.3 per cent leakage more pronounced in difficult terrain. Fourth, the IAI of 0.04 indicates a critical deficiency in downstream infrastructure. Fifth, the baling-to-co-processing pathway (operational since 2024) demonstrates that proximity to cement kilns can serve as engineered disposal infrastructure for small hill municipalities.

6. CONCLUSIONS

This study uses a systems-based approach to analyse household survey data, secondary information on waste generation and composition, and a set of simple performance indicators such as CCR, SLR, DFAI, SSE, and IAI. These indicators provide a broad understanding of the existing municipal solid waste management system and help identify major gaps and planning needs. The framework is mainly intended as a diagnostic and planning tool that converts survey findings into preliminary estimates for infrastructure planning. It does not represent a complete engineering design study.

The study does not include several components that are normally part of a detailed systems engineering analysis. For example, it does not examine vehicle routing, fleet optimisation, collection scheduling, time-and-motion studies, cost modelling, or detailed engineering design of waste processing facilities. Similarly, field-based material flow measurements were not carried out. As a result, the findings should be viewed as an initial assessment that can support planning rather than provide final engineering solutions. Detailed engineering design, financial evaluation and operational optimisation should be undertaken before any proposed interventions are implemented.

The terrain classification developed in this study, which groups areas into Categories A, B and C based on slope and road width, is presented as a conceptual framework to relate local terrain conditions with suitable waste collection systems and vehicle requirements. However, the analysis was not carried out at the ward level. A more detailed assessment of individual wards, including variations in slope, road width, waste collection coverage and system losses, would provide a clearer understanding of local challenges and help improve planning and resource allocation.

The proposed capacities for waste management facilities, including composting units, Material Recovery Facilities (MRFs), sanitary landfill requirements and pharmaceutical waste incineration, are preliminary estimates derived from available waste generation and composition data. These estimates are intended to support initial planning and decision-making rather than serve as final design values. Before infrastructure is developed, detailed site investigations, geotechnical studies, field-based waste characterisation, mass-balance analysis, engineering design and cost-benefit assessment should be carried out to ensure that the proposed facilities are technically suitable, economically feasible and environmentally sustainable

This study shows that small hill towns can achieve high levels of household compliance when waste collection systems are consistent and well-designed. The door-to-door model effectively normalises source segregation practices, even without extensive prior awareness campaigns. However, strong performance in collection alone does not ensure environmental protection. Efficient collection, in the absence of adequate treatment capacity, simply relocates pollution from households to dumping sites. By applying a systems engineering framework, this study translates household-level survey findings into practical infrastructure design parameters. The baling-to-co-processing system at BMC further illustrates that proximity to cement kilns can serve as a cost-effective and replicable engineered disposal pathway for similar hill towns. As outlined above, the specific infrastructure capacities and design parameters proposed here are planning-level estimates intended to guide preliminary decision-making, and should be validated through direct field measurement and detailed engineering design before implementation.

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