

Article

Monitoring Municipal Solid Waste Along the Collection Chain: Composition and Property Shifts from Source to Communal Storage and Dumpsite in Sialkot, Pakistan

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Abstract

Municipal waste composition is commonly measured at a single point, even though recovery, mixing and handling can alter the stream before disposal. This study examined municipal solid waste in Sialkot, Pakistan, during an eight-day campaign from 27 December 2021 to 3 January 2022. A total of 672 physical-characterization samples was obtained from residential, commercial, institutional, industrial and street-sweeping sources. Household generation was 0.42, 0.46 and 0.51 kg per person per day in low-, middle- and high-income proxy areas, respectively. Kitchen waste declined from 45.91% at the source to 34.20% at communal storage and 23.45% at the dumpsite. Recyclable paper and plastic also declined, whereas dust and fines increased from 2.05% at the source to 19.60% at storage and 21.78% at disposal. Six mixed-waste composites showed moisture contents of 30.72–53.06%, ash contents of 15.85–45.04% and gross calorific values of 2924–12,530 kcal kg^{−1}. The results demonstrate that monitoring location materially affects estimated recycling and treatment potential. A multi-point monitoring protocol is therefore recommended for cities with mixed collection and informal material recovery.

Keywords: municipal solid waste; waste characterization; informal recycling; communal storage; material recovery; Pakistan



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1. Introduction

Reliable information on municipal solid waste generation and composition is essential for collection planning, recycling-system design, biological treatment, energy recovery and final disposal [1,2]. Such information is nevertheless sensitive to sampling boundaries, collection practices, and the point at which the waste is observed [3]. In low- and middle-income cities, municipal systems commonly combine formal collection with informal extraction of valuable materials, variable service coverage and open or controlled dumping [4–8]. Consequently, a sample collected from a communal container or disposal site may not represent the material originally generated at households, businesses or institutions.

Waste-characterization studies usually focus on generation rates, socio-economic differences, seasonal effects, or composition at a single system stage [9–12]. Studies from Pakistan have documented substantial differences in generation and composition among income groups and seasons [10,11]. Research on informal recycling has also shown that paper, metals and selected plastics may be removed at households, during collection, at communal storage or at disposal sites [5–7,13–15]. These transactions can reduce the recoverable fraction observed downstream while increasing the relative share of contaminated plastics, diapers and inert material.

The reduce–reuse–recycle concept prioritizes prevention and direct reuse before material recycling. Its practical assessment requires a clear system boundary: downstream composition alone cannot show the quantity of recyclables already recovered upstream. Likewise, high food-waste fractions measured at the source may not remain equally available after storage and collection, particularly when street sweepings and fine inert material are mixed into communal containers. Developing-Asia evidence indicates that high organic and moisture contents generally support biological treatment, whereas high moisture and ash can constrain direct thermal recovery [8,16–19].

A clear knowledge gap remains in studies that compare physical composition and bulk properties at several points within the same municipal collection chain. Most published characterization studies provide detailed source-level or disposal-level results, but fewer examine how the measured stream changes from generation through communal storage to final disposal. This gap is important for cities where informal recovery and mixed collection occur simultaneously, because investment decisions based on a single monitoring point may overestimate or underestimate recycling, composting and energy-recovery feedstocks.

The objective of this study was to quantify and interpret stage-wise differences in municipal solid waste in Sialkot, Pakistan. The specific aims were to: (i) document the distribution of an eight-day, 672-sample characterization campaign; (ii) compare composition at the source, communal storage and the dumpsite; (iii) compare moisture, ash, carbon-to-nitrogen results and gross calorific value for mixed-waste composites; and (iv) derive transparent descriptive indicators for routine monitoring. The contribution is a transferable chain-aware monitoring approach for lower-middle-income cities that use communal storage and experience informal material recovery.

2. Results

2.1. Sampling Coverage and Household Generation

The campaign covered eight consecutive days, from Monday 27 December 2021 to Monday 3 January 2022. Eighty-four samples were obtained per day, producing 672 physical-characterization samples. The sample distribution is given in Table 1. Residential sampling comprised 20 households in each income-proxy area; each household contributed one daily sample, yielding 160 samples per residential class. Commercial, institutional and industrial sources were sampled daily over the same period.

The three residential classes each included 20 households and 120 residents. The cumulative eight-day household waste masses were 403.2 kg in Haji Pura Camp, 441.6 kg in Shahab Pura and 489.6 kg in Model Town. These values corresponded to 0.42, 0.46 and 0.51 kg person^{−1} day^{−1}, respectively. The arithmetic mean of the three class-specific rates was 0.46 kg person^{−1} day^{−1}.

Table 1. Distribution of physical-characterization samples during the eight-day campaign.

Source Category	Subcategory/Area	Sampling Point	Locations (<i>n</i>)	Samples (<i>n</i>)
Residential	Lower-income residential	Haji Pura Camp	1	160
Residential	Middle-income residential	Shahab Pura	1	160
Residential	Higher-income residential	Model Town	1	160
Commercial	Restaurants	Five establishments	5	40
Commercial	Other commercial units	Five establishments	5	40
Institutional	Schools, colleges and offices	Five institutions	5	40
Industrial	Industrial units	Karim Pura/Shah Syadan	8	64
Street sweeping	Street-sweeping sample	City sampling stream	1	8
Total			22	672

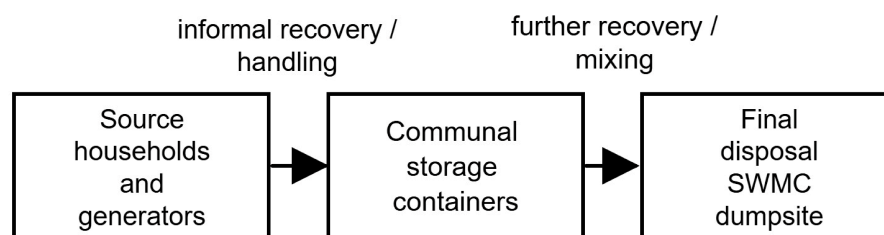
2.2. Composition at Source, Communal Storage and Disposal

The reported composition differed substantially among the three monitoring points (Table 2). Because the available dataset contains rounded aggregate percentages rather than sample-level observations, the results are described as stage-wise differences rather than statistically tested trends.

Table 2. Physical composition at source, communal storage and the dumpsite (% by mass).

Fraction	Source	Communal Storage	Dumpsite
Kitchen waste	45.91	34.2	23.45
Recyclable paper	5.24	1.3	0.12
Non-recyclable paper	1.59	2.0	0.29
Recyclable plastic	2.73	0.3	0.13
Non-recyclable plastic	9.86	14.3	16.75
Diapers	15.76	20.9	21.78
Rubber and leather	0.07	0.4	0.0
Glass	1.81	0.0	0.2
Metal	1.68	0.0	0.0
Wood	0.05	0.5	0.31
Textile	6.99	6.1	8.04
Inert/construction debris	1.29	0.3	6.7

Kitchen waste remained the largest fraction but declined from 45.91% at source to 34.20% at communal storage and 23.45% at the dumpsite. Recyclable paper decreased from 5.24% to 1.30% and 0.12%, while recyclable plastic decreased from 2.73% to 0.30% and 0.13%. In contrast, dust and fines increased from 2.05% at source to 19.60% at storage and 21.78% at the dumpsite. Non-recyclable plastic and diapers also represented larger shares downstream. The equal dumpsite values reported for diapers and dust and fines (21.78% each) were retained exactly as recorded; the aggregate data do not permit confirmation of whether the equality arose from rounding or the underlying measurements. The Figure 1 illustrates key monitoring points throughout the municipal solid waste collection chain and the processes that can influence waste composition measurements. The Figure 2 compares the stage-wise proportions of four decision-relevant waste fractions across the municipal solid waste collection chain. The Figure 3 presents the complete 16-fraction waste composition across monitoring points using grouped horizontal bars.



Composition and bulk properties may change between monitoring points

Figure 1. Monitoring points along the municipal solid waste collection chain and the main processes that may alter measured composition.

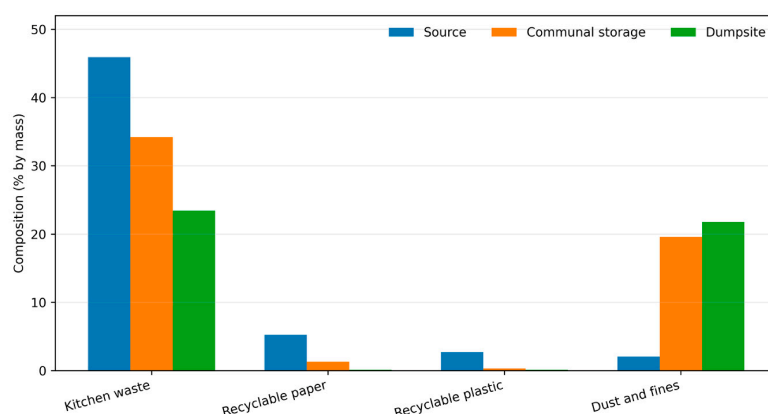


Figure 2. Stage-wise differences in four decision-relevant waste fractions. Values are reported percentages; no inferential trend test was performed.

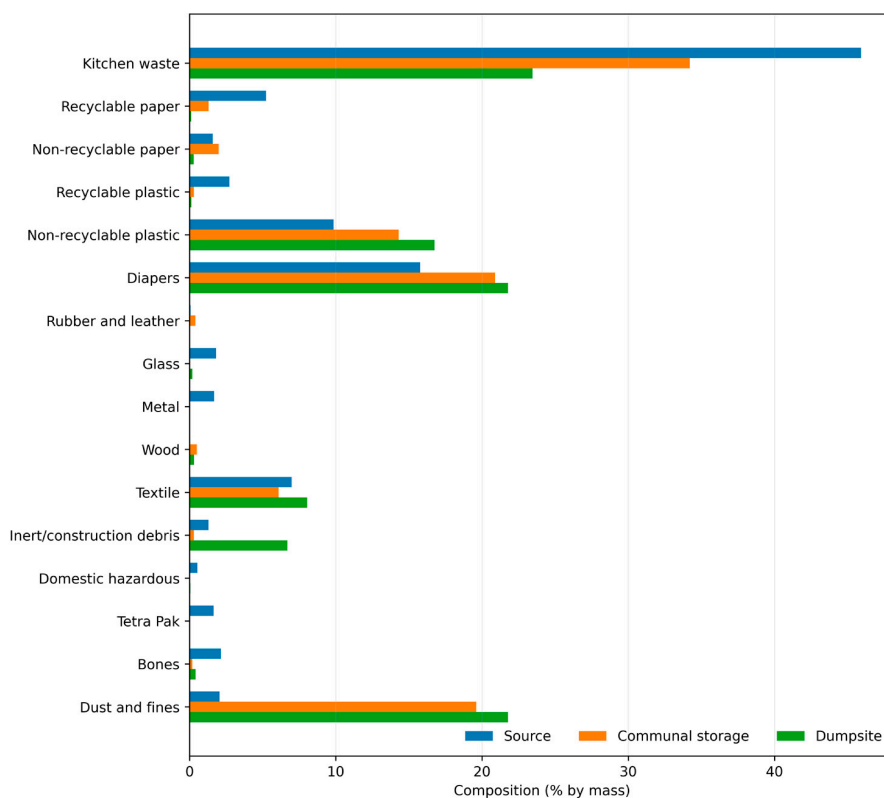


Figure 3. Full 16-fraction composition shown as grouped horizontal bars. The three colours represent monitoring points rather than individual fractions.

2.3. Bulk Density and Laboratory Properties

The source-waste bulk density reported in the project records was 250–300 kg m^{−3}. One field composite and one laboratory composite were available for each of the six sampling points. A 100 g analytical portion from each laboratory composite was used for moisture, ash, carbon and nitrogen, and gross calorific value determinations (Table 3).

Table 3. Laboratory properties of mixed municipal solid waste composites.

Sampling Point	Moisture (%)	Ash (%)	Carbon (%):Nitrogen (%)	Gross Calorific Value (kcal kg ^{−1})
Container	53.06	25.17	10.01:2.20	2924
Dumpsite	47.14	15.85	19.2:3.01	4510
Middle-income area	42.1	45.04	8.30:3.20	5670
Higher-income area	44.21	15.96	14.2:3.30	6425
Industrial source	30.72	35.78	11.4:3.20	12,530
Lower-income area	43.0	45.02	6.73:1.08	3518

Moisture ranged from 30.72% for the industrial composite to 53.06% for the container composite. Ash ranged from 15.85% at the dumpsite to 45.04% in the middle-income composite. Gross calorific value ranged from 2924 kcal kg^{−1} for container waste to 12,530 kcal kg^{−1} for industrial waste. These are point-specific screening values from single composites and should not be interpreted as population estimates with statistical uncertainty.

2.4. Descriptive Chain-Monitoring Indicators

Four descriptive ratios were calculated from the rounded aggregate percentages. For a selected fraction, the downstream retention ratio was calculated as the downstream percentage divided by the source percentage. For dust and fines, the storage contamination factor was calculated as the storage percentage divided by the source percentage. These ratios were created for transparent operational comparison; they are not presented as standardized indices from an external method. Table 4 provides the detail for the indicators derived from the aggregate composition value.

Table 4. Descriptive indicators derived from the aggregate composition values.

Indicator	Calculation	Operational Interpretation
Recyclable-paper retention at dumpsite	0.12/5.24 = 0.02	Only about 2% of the source percentage remained visible at disposal
Recyclable-plastic retention at dumpsite	0.13/2.73 = 0.05	Only about 5% of the source percentage remained visible at disposal
Kitchen-waste retention at dumpsite	23.45/45.91 = 0.51	The dumpsite percentage was approximately half the source percentage
Dust/fines storage factor	19.60/2.05 = 9.56	The storage percentage was approximately 9.6 times the source percentage

3. Discussion

3.1. Waste Generation and Composition in Relation to Published Evidence

The household generation range of 0.42–0.51 kg person^{−1} day^{−1} is compatible with the lower part of ranges reported for Pakistani cities, although comparisons depend strongly on the inclusion of commercial waste, sampling duration and season. Islamabad research reported 0.346, 0.612 and 0.890 kg person^{−1} day^{−1} for low-, middle- and high-income groups, respectively, and demonstrated significant seasonal effects [11]. The lower and

narrower Sialkot range may reflect the household-only boundary, winter campaign and the use of built-environment proxies. It should not be interpreted as an annual citywide rate.

The source kitchen-waste share of 45.91% is consistent with the high biodegradable content commonly reported in lower-middle-income settings. Ghanaian municipal waste contained approximately 61% organics [12], while studies in developing Asia commonly report organic fractions exceeding 50% [8]. Pakistani studies likewise describe organic-rich and moisture-rich waste [10,11,16]. The lower kitchen-waste share observed at Sialkot's communal storage and dumpsite illustrates why source and downstream composition should not be treated as interchangeable.

The sharp downstream reduction in recyclable paper and plastic is consistent with multi-stage value recovery. Informal-sector studies show that recyclable materials may be extracted by households, itinerant buyers, collection workers, waste pickers at containers and actors at disposal sites [5–7,13–15]. The present study did not track individual material flows or survey recovery actors; therefore, the result is evidence of stage-wise depletion consistent with recovery, not a direct measurement of diversion. Nevertheless, the magnitude of the difference indicates that a material recovery facility designed from dumpsite composition alone would underestimate the recyclable content originally present at the source.

The increase in dust and fines at communal storage is operationally important. Street sweepings formed a separately sampled stream in the campaign, while communal containers received mixed waste within the municipal system. Mixing sweepings with container waste can increase ash, dilute biodegradable and recyclable fractions, reduce compost quality and increase residues requiring disposal. Similar difficulties arise in developing-city systems where collection boundaries and handling practices influence measured composition [4,8]. Separate routing or timed collection of street sweepings would therefore improve both monitoring accuracy and downstream feedstock quality.

The laboratory results also fall within the broad variability reported for Pakistani waste, but the single-composite design limits formal comparison. Ilmas et al. reported moisture contents of approximately 40–53% for urban waste from Lahore and Rawalpindi [16], which overlaps the Sialkot range of 30.72–53.06%. The higher ash values in the middle- and lower-income composites may reflect inert contamination, fuel ash, soil or fine material. The wide gross calorific value range, especially the high industrial value, confirms that generator type strongly affects energy content. Pakistani energy studies emphasize that moisture, ash and separation of combustible fractions are critical to thermal feasibility [17,18]. Consequently, the 12,530 kcal kg^{−1} industrial value should not be extrapolated to mixed municipal waste, while the 2924 kcal kg^{−1} container value illustrates the penalty associated with wet and contaminated feedstock.

From a recycling perspective, the findings support intervention upstream rather than exclusive reliance on residual waste at the dumpsite. Source-segregated collection from markets, restaurants and selected neighbourhoods could retain cleaner food waste for composting or anaerobic digestion. Formal–informal integration at collection and communal-storage points could improve occupational conditions and record recovered quantities without removing established livelihoods. For recyclable dry materials, pilot buy-back or designated sorting arrangements would provide a more realistic basis for formal recovery than a downstream facility supplied mainly with residual waste.

The monitoring approach is transferable to other lower-middle-income cities with mixed collection, communal containers and informal recycling. Transferability lies in the protocol rather than in the numerical percentages: consistent fraction definitions, simultaneous source/storage/disposal observations, documentation of sample counts and weights, and a limited set of transparent ratios. Repeating the campaign in contrasting

seasons and retaining sample-level data would allow statistical testing and uncertainty intervals in future rounds.

3.2. Limitations

The study represents an eight-day winter snapshot and cannot characterize annual or seasonal variability. The retrieved field data identify the distribution of all 672 source-characterization samples, but exact individual sample weights for physical sorting were not retained. Catchment populations for communal containers and point-specific daily waste quantities were also unavailable. The operational estimate of approximately 400 t day⁻¹ refers to the wider municipal service system rather than measured waste at each sampling point. Exact origin routes and vehicle types for the selected dumpsite loads were not retained in the recovered worksheet. Laboratory results are based on one field composite and one laboratory composite per sampling point, with one 100 g analytical portion; no replicate-based uncertainty can therefore be calculated. Finally, exact fraction-specific recombination weights used to prepare the mixed laboratory composites were not documented. These limitations are now reported explicitly and constrain the analysis to descriptive stage-wise comparison.

4. Materials and Methods

4.1. Study Area, Municipal System and Campaign Period

Sialkot is an industrial and commercial city in Punjab, Pakistan. During the 2021–2022 study period, the municipal solid waste management service area represented approximately 869,565 people over 45.2 km². The municipal system handled approximately 400 t day⁻¹ through a mixed arrangement of household collection, communal storage and transport by Sialkot Waste Management Company vehicles to the existing dumpsite. No formal citywide source-separation system was documented; informal recovery occurred at the source, during collection, at storage points and at disposal. The characterization campaign was conducted over eight consecutive days from 27 December 2021 to 3 January 2022. Programme and city context were obtained from project records and relevant provincial planning documents [20–24].

4.2. Sampling Design and Source Distribution

Physical characterization covered 22 locations or source units: one lower-income residential locality (Haji Pura Camp), one middle-income locality (Shahab Pura), one higher-income locality (Model Town), five restaurants, five other commercial establishments, five institutions, eight industrial units in Karim Pura and Shah Syadan, and one street-sweeping sampling stream. Residential classes were project-defined income proxies based on observable built-environment and lifestyle characteristics: smaller houses, narrower streets and comparatively lower infrastructure quality for the lower-income proxy; intermediate characteristics for the middle-income proxy; and larger houses, wide paved streets and better infrastructure for the higher-income proxy. These classifications were used for sampling stratification and were not household income measurements.

Each selected source was sampled once per day for eight days. Residential sampling included 20 households in each locality, providing 20 daily household samples and 160 samples per class. Five restaurants, five other commercial units, and five institutions each provided one daily sample, producing 40 samples per category. Eight industrial units each provided one daily sample, producing 64 samples. One street-sweeping sample was obtained per day, producing eight samples. The resulting total was 84 samples per day and 672 samples over the campaign.

4.3. Household Generation Calculation

The load-and-count calculation divided the cumulative measured household waste mass by the product of the recorded resident count and the eight-day collection duration [3]. Household occupancy was obtained through the campaign's household records. For each income-proxy class, 20 households with a combined 120 residents were monitored. The calculation was: generation rate ($\text{kg person}^{-1} \text{ day}^{-1}$) = cumulative waste mass (kg)/[resident count $\times$ monitoring days]. Thus, $403.2/(120 \times 8) = 0.42$, $441.6/(120 \times 8) = 0.46$ and $489.6/(120 \times 8) = 0.51 \text{ kg person}^{-1} \text{ day}^{-1}$.

4.4. Physical Sorting and Quality Control

Waste samples were processed at the Iqbal Town Workshop and the Sialkot Waste Management Company parking area. Sorting followed a fixed 16-fraction list and principles of standard municipal waste characterization [2,9,25]. Fractions were manually separated, weighed and expressed as a percentage of the sorted mass. Recyclable paper and plastic denoted locally marketable grades, whereas non-recyclable categories represented contaminated or low-value materials. Dust and fines comprised fine inert particles and sweepings material. Labels and definitions were maintained throughout the campaign, and on-site supervision was used to check gross misclassification and completeness of recording.

4.5. Communal-Storage and Dumpsite Sampling

Communal-storage composition was obtained from mixed waste at communal collection points within the city. The available field workbook does not retain a fixed catchment population for these containers; users originated from neighbourhoods and collection routes rather than a closed household list. Dumpsite extraction was conducted over two days and covered morning and afternoon operating periods. Every tenth arriving vehicle was selected to reduce discretionary selection. Selected loads were spread without excessive crushing, turned five times, and material was taken from ten distributed positions across the load. The gross material was combined and reduced through coning and quartering to the sorting mass. The recovered worksheet does not preserve route-zone or vehicle-type identifiers for the selected loads; this absence is reported as a limitation rather than reconstructed.

4.6. Laboratory Composite Preparation and Testing

Six sampling points were represented in laboratory testing: lower-income, middle-income, higher-income, industrial, communal-container and dumpsite waste (Supplementary File S1). For each point, one field composite was used to prepare one mixed-waste laboratory composite. Sorted fractions were recombined to represent the overall stream at that point and then reduced for testing; however, exact fraction-specific recombination masses were not retained. A 100 g analytical portion was used for each reported laboratory composite. Moisture, ash, carbon and nitrogen, and gross calorific value were determined using ASTM D3163-11, D3174-11, D5373-14 and D5865-13, respectively [26–29].

4.7. Data Analysis

Sample counts, household totals and laboratory metadata were verified against the recovered field-data workbook. Composition percentages and laboratory values were taken from the project and laboratory reports. Because sample-level composition values and replicate laboratory measurements were not available, no hypothesis tests, confidence intervals or citywide weighting were applied. Analysis was limited to descriptive comparison. Downstream retention ratios were calculated as downstream percentage/source percentage,

and the dust/fines storage factor was calculated as storage percentage/source percentage. Ratios were rounded to two decimal places and interpreted only as operational indicators.

5. Conclusions

The Sialkot campaign demonstrates that municipal waste measured at the source, communal storage and final disposal can differ sufficiently to alter recycling and treatment decisions. Across 672 source-characterization samples, household generation ranged from 0.42 to 0.51 kg person^{−1} day^{−1}. Kitchen waste, recyclable paper and recyclable plastic were progressively less prominent downstream, whereas dust and fines increased sharply at communal storage and remained high at disposal. Laboratory composites showed large differences in moisture, ash and gross calorific value among generator and chain points. These observations fill a practical literature gap by linking source-level characterization with downstream monitoring in a city where mixed collection and informal recovery coexist. The numerical results are specific to the eight-day winter campaign, but the multi-point protocol is transferable to comparable lower-middle-income cities. Future work should repeat sampling across seasons, retain individual weights and route identifiers, document container catchments, and include replicate laboratory analyses.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/recycling11080137/s1>, File S1: Municipal Solid Waste Analysis Report: Lower, Middle, Higher, Container, Dumpsite and Industry.

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