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Physical Characterization and Resource-Recovery Potential of Municipal Solid Waste at Transfer Stations and a Landfill in Karachi, Pakistan

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ABSTRACT

Municipal solid waste (MSW) characterization is needed to select recovery and disposal options that reflect local waste streams. This study characterized 20 MSW samples from three garbage transfer stations and Jam Chakro disposal site in Karachi, Pakistan, using manual sorting based on ASTM D5231-92. Five samples were analyzed at each site; sample masses ranged from 92 to 105 kg, with 1,988 kg characterized overall. Pooled composition was dominated by other inorganics/non-combustibles (36.3%), plastic (19.7%), food waste (13.4%), other organics/combustibles (12.0%), yard waste (7.6%), and diapers/sanitary products (6.7%). Sample-level analysis showed significant between-site differences in food waste, corrugated material, and other inorganics after false-discovery-rate adjustment. Film represented 95.5% of the plastic fraction. Results support source segregation and targeted recovery, while transfer-to-landfill differences cannot be attributed solely to informal scavenging because waste loads were not paired.

Keywords: Municipal solid waste; Waste characterization; Resource recovery; Garbage transfer stations; Karachi

1. INTRODUCTION

Municipal solid waste (MSW) characterization is a practical starting point for designing a waste-management system because treatment and recovery options depend on the materials that are actually present in the waste stream. The proportions of biodegradable matter, plastics, paper, metals, glass, combustibles and inert material affect collection requirements, material-recovery potential, biological treatment, energy-recovery options and landfill demand. For this reason, direct characterization of local waste streams remains necessary even where citywide generation estimates are available (Chang & Davila, 2008; Kaza et al., 2018).

Karachi presents a difficult setting for such planning because waste estimates and measured compositions vary with the study period, source and analytical boundary. A material-flow assessment of the city reported substantial losses and informal recovery within the existing system, showing that waste arriving at final disposal does not necessarily represent the composition of waste originally generated (Aslam et al., 2022). Shahid et al. (2022) likewise reported marked seasonal changes in Karachi MSW and described plastics as one of the major fractions after organic waste. More recent field work in District East has again demonstrated that local composition and operational conditions vary across collection and transfer locations (Hassan et al., 2026). These studies make a strong case for site-specific measurements rather than reliance on a single citywide composition profile. Variation is not limited to Karachi. In Islamabad, Zia et al. (2017) found that both income level and season influenced MSW quantity and composition. Such variability matters because an apparently favourable fraction for composting, recycling or energy recovery in one campaign may not be representative throughout the year. The same concern applies to data collected at different points in a waste-management chain: transfer-station material may contain components that are subsequently removed, mixed, degraded or contaminated before final disposal.

Informal recovery is an important part of this chain in Pakistan. Asim et al. (2012) documented the role of scavengers in recovering recyclable materials in Lahore, while the Karachi material-flow analysis by Aslam et al. (2022) identified informal recovery as an important pathway for recyclable materials. This creates a plausible reason for differences between transfer-station and landfill composition. However, composition differences alone cannot establish causation. To demonstrate a scavenging effect rigorously, the same waste loads would need to be followed through the transfer and disposal process, or a controlled mass balance would be required. Published work has also examined the energy and disposal implications of Karachi and Pakistan MSW. Siddiqi et al. in 2019 evaluated the energy potential of municipal waste in urban Pakistan, while Sohoo et al. in 2021 assessed biochemical methane potential for Karachi waste. further examined landfill-based management and greenhouse-gas implications for Karachi (Siddiqi et al. 2019, Sohoo et al. 2021). Together, this literature shows that physical composition is a useful screening variable, but it is not sufficient on its own to confirm technical feasibility for composting, refuse-derived fuel, incineration or anaerobic digestion; moisture, calorific value, contamination, process performance and economics are also required.

The present study therefore focuses on the physical composition of MSW at three garbage transfer stations (GTSs) and Jam Chakro landfill/disposal site in Karachi.

The objectives were to: (i) quantify the mass fraction and variability of major MSW components using the available sample-level data; (ii) compare composition among the four sampled sites; (iii) describe changes between the combined GTS samples and the landfill samples without assigning unsupported causality; (iv) characterize the plastic sub-fractions recorded during sorting; and (v) develop a transparent, composition-based screening of material groups that may warrant further assessment for recovery, biological treatment, energy recovery or residual disposal.

2. MATERIALS AND METHODS

2.1 Study design and sites

The study was a cross-sectional physical characterization of mixed MSW at four locations in Karachi. Three transfer-station datasets were identified in the original study report as GTS Baldia, GTS Sharafi and GTS Truck Stand, and the disposal-site dataset was from Jam Chakro. Five samples were characterized at each location, giving 20 samples in total. The detailed raw-data sheet uses working labels for two sample groups, while the reporting summary in the same workbook identifies the corresponding 497.0-kg and 476.0-kg groups as Mean Sharafi and Mean TS, respectively. These totals and components mean reconcile with the original report, so the report-level site names are used throughout without changing any numerical observations.

2.2 Field sampling and sorting

The field procedure was based on manual sorting principles in ASTM D5231-92(2016) (ASTM International, 2016). Mixed waste was reduced and handled using coning and quartering, with hand shovels and mechanical excavation used during sample preparation where required. The field equipment recorded in the original study included 25-L plastic buckets, calibrated weighing scales (200 kg and 5 kg capacities), tarpaulin sheets, personal protective equipment and a calibrated 200-L plastic drum used during weighing. Because the surviving field dataset does not document the exact sampling dates or the temporal interval over which the 20 samples were collected, the work is described as being based on ASTM D5231-92 rather than as a claim of complete conformance with every temporal sampling requirement of the standard.

Individual sample masses ranged from 92.0 to 105.0 kg. Site totals were 512.0 kg at Baldia, 497.0 kg at Sharafi, 476.0 kg at Truck Stand and 503.0 kg at Jam Chakro, for an overall sampled mass of approximately 1,988.0 kg. A single 0.45-kg e-waste observation was recorded in the raw workbook. It was retained as a separate observation and excluded from the 13 principal physical categories used in the original analysis; it represented approximately 0.02% of the total sampled mass.

2.3 Data preparation and category aggregation

The raw workbook contained both main categories and sub-categories. To reproduce the analytical structure used for the original graphs and manuscript, sub-categories were consolidated before calculating mass fractions. The mixed-paper group included the recorded mixed paper, high-grade paper, computer printout, other office paper and tissue entries. The corrugated group included corrugated material and Tetra Pak entries as they had been combined in the original analysis. Plastic was calculated as the sum of PET bottles, HDPE bottles, film and other plastic. Ferrous material combined cans and other ferrous entries; aluminium combined cans, foil and other aluminium; and glass combined clear, brown and green glass. Food waste, wood, other organics/combustibles, other inorganics/non-combustibles, yard waste and diapers/sanitary products were retained as recorded.

For each sample, component mass fraction was calculated as 100 multiplied by component mass divided by the measured total sample mass. Site results are reported as mean ± standard deviation (SD) for the five samples. A pooled mass fraction was also calculated by dividing the total mass of each component across all samples by the total sampled mass. Because the separate 0.45-kg e-waste observation was not assigned to a principal category, the 13 pooled fractions sum to approximately 99.98% rather than exactly 100%.

2.4 Statistical analysis

Between-site differences were assessed at the sample level. The small group size ($n = 5$ per site), zero values in several components and non-normal appearance of some fractions did not justify relying on parametric analysis of variance. Kruskal-Wallis tests were therefore applied separately to the 13 principal component percentages across the four sampled sites. To control the false discovery rate arising from multiple component-wise tests, Benjamini-Hochberg adjustment was applied to the 13 p-values. Adjusted q-values below 0.05 were treated as statistically significant. The tests were exploratory and were not interpreted as evidence for a general difference between facility types because only one landfill site was sampled.

The combined GTS-versus-landfill comparison was consequently descriptive: the 15 transfer-station samples were summarized as mean ± SD and compared with the five Jam Chakro samples without a facility-type hypothesis test. Plastic sub-fractions were expressed as percentages of the plastic mass within each sample. All reported statistics were recalculated from the supplied raw workbook rather than from the earlier graph-level summary tables.

2.5 Composition-based resource-recovery screening

A simple screening allocation was prepared from the pooled physical composition. Mixed paper, newsprint, corrugated/cardboard, plastic, wood and other organics/combustibles were grouped as potentially combustible material for subsequent energy-recovery assessment. Food and yard waste were grouped for biological-treatment screening. Ferrous metals, aluminium and glass were grouped as measured recoverable materials, and other inorganics/non-combustibles plus diapers/sanitary products were grouped as residual material. These groups are indicative only. They do not represent actual diversion rates, recoverable yields or proven process feasibility.

3. RESULTS

3.1 Sample mass and overall composition

The 20 samples represented approximately 1,988.0 kg of mixed MSW. Mean sample masses were 102.4 kg at Baldia, 99.4 kg at Sharafi, 95.2 kg at Truck Stand and 100.6 kg at Jam Chakro (Table 1). The pooled composition was dominated by other inorganics/non-combustibles (36.32%) and plastic (19.71%). Food waste represented 13.44%, other organics/combustibles 11.96%, yard waste 7.61% and diapers/sanitary products 6.74%. Each remaining principal component contributed less than 2% of pooled mass (Table 2; Figure 1). Across the 20 individual samples, the largest between-sample variability was observed for other inorganics/non-combustibles (overall mean 36.18 ± 9.65%) and food waste (13.46 ± 6.59%).

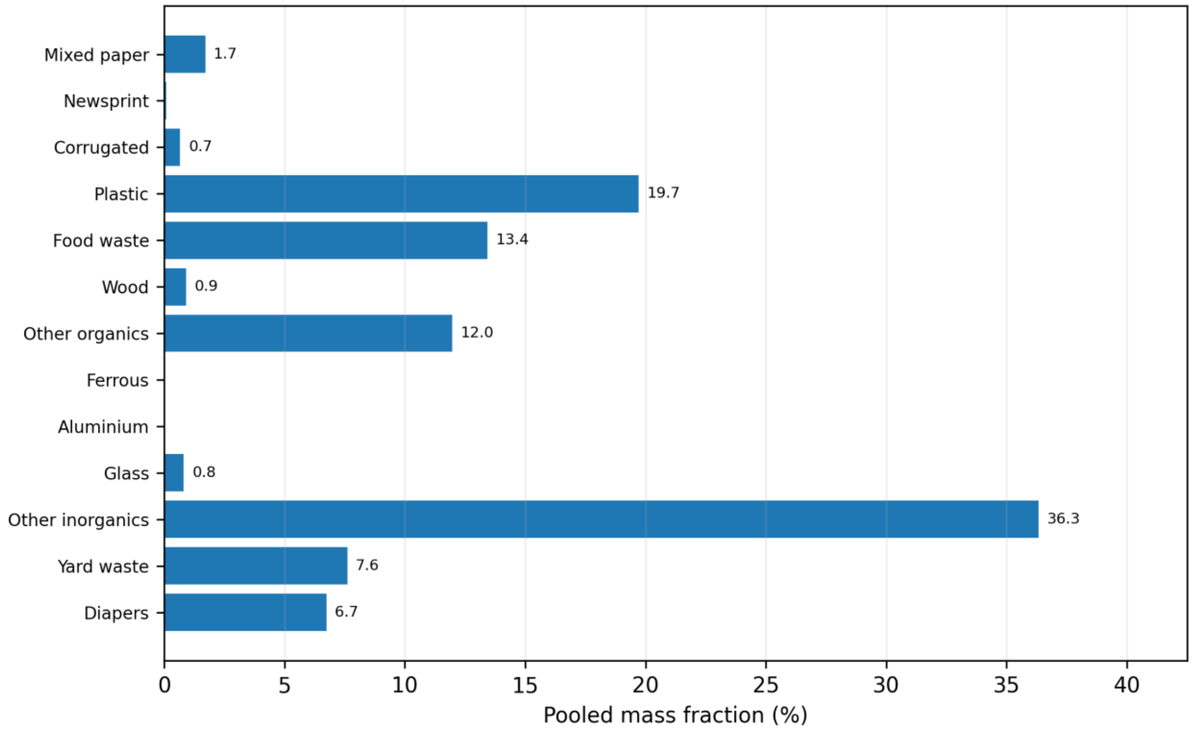

Figure 1. Pooled mass fractions of the 13 principal municipal solid waste components across the 20 samples (total sampled mass approximately 1,988 kg). A separate 0.45-kg e-waste observation is not included in the 13 bars.

3.2 Site-specific composition and between-site differences

Composition varied materially among the four sampled sites. Plastic averaged 21.39 ± 4.12% at Baldia, 19.20 ± 0.51% at Sharafi, 21.77 ± 1.58% at Truck Stand and 16.61 ± 4.98% at Jam Chakro. Food waste averaged 18.04 ± 2.73%, 12.85 ± 3.42%, 18.22 ± 5.82% and 4.72 ± 1.69%, respectively. In contrast, other inorganics/non-combustibles were highest at Jam Chakro (50.54 ± 3.24%) compared with 34.43 ± 4.39% at Baldia, 32.84 ± 3.35% at Sharafi and 26.91 ± 4.29% at Truck Stand.

After Benjamini-Hochberg adjustment across the 13 component-wise Kruskal-Wallis tests, three fractions retained significant between-site differences: corrugated/cardboard ($H = 13.64$, $p = 0.0034$, $q = 0.020$), food waste ($H = 13.01$, $p = 0.0046$, $q = 0.020$) and other inorganics/non-combustibles ($H = 14.15$, $p = 0.0027$, $q = 0.020$).

Mixed paper and wood had nominal p-values below 0.05 but did not remain significant after false-discovery-rate adjustment (Table 3; Figure 2). No significance claim is made for the remaining components.

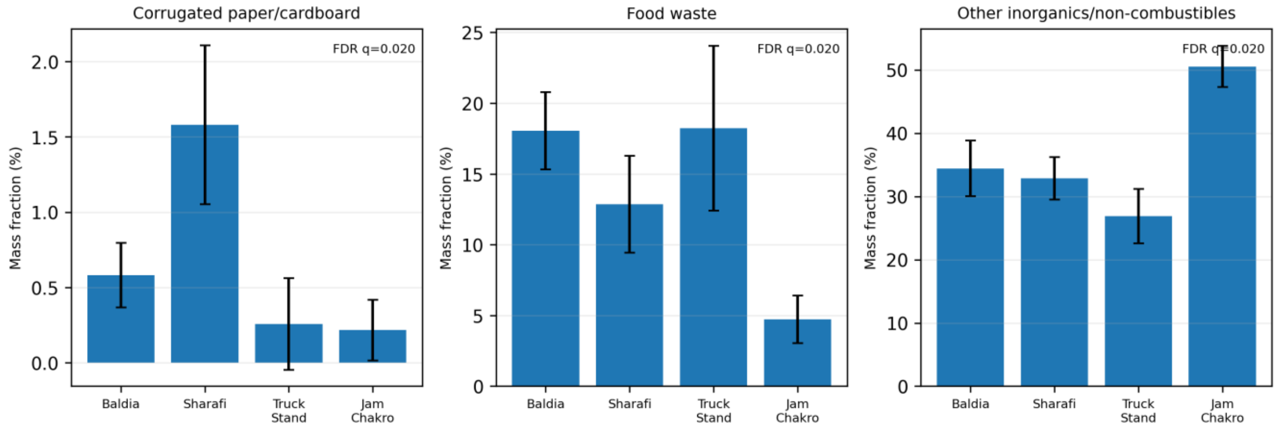

Figure 2. Site-specific mean ± SD mass fractions for the three components that remained significantly different among the four sampled sites after Benjamini-Hochberg false-discovery-rate adjustment (n = 5 samples per site).

3.3 Plastic sub-fractions

Film dominated the measured plastic fraction. Across all 20 samples, film represented 95.47 ± 2.20% of plastic mass on a sample-level basis, with a pooled share of 95.45%. Other plastic represented a pooled 3.49%, HDPE bottles 0.84% and PET bottles 0.22%. The mean film share ranged from 93.17% at Sharafi to 97.24% at Jam Chakro (Table 4; Figure 3). The result indicates that the plastic remaining in the mixed waste stream was overwhelmingly flexible-film material rather than PET or HDPE bottles.

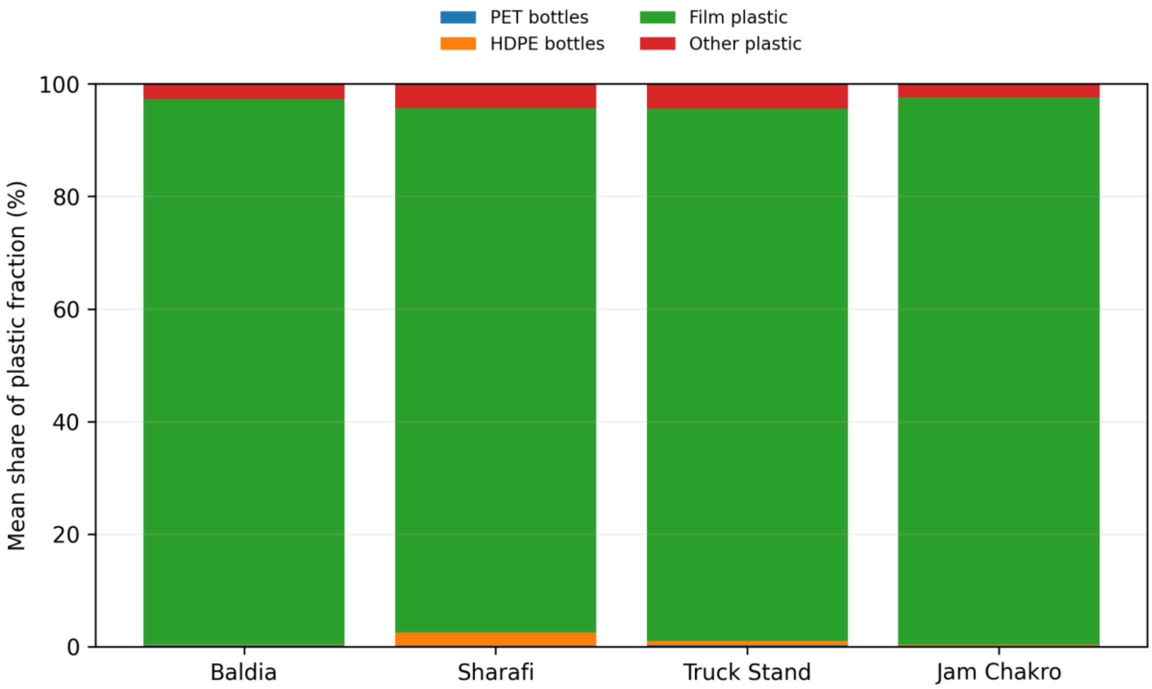

Figure 3. Mean plastic sub-fraction composition at the four sampled sites, expressed as percentage of plastic mass. Film plastic dominated the measured plastic fraction at every site.

3.4 Descriptive comparison of transfer-station and landfill samples

When the 15 GTS samples were pooled descriptively, plastic averaged 20.79 ± 2.65% compared with 16.61 ± 4.98% at Jam Chakro; food waste averaged 16.37 ± 4.67% compared with 4.72 ± 1.69%; corrugated/cardboard averaged 0.81 ± 0.68% compared with 0.22 ± 0.20%; and glass averaged 1.01 ± 0.82% compared with 0.23 ± 0.23%. Other inorganics/non-combustibles showed the opposite pattern, averaging 31.39 ± 5.02% across GTS samples and 50.54 ± 3.24% at Jam Chakro. Other organics/combustibles were slightly higher at Jam Chakro

(13.07 ± 4.21%) than across GTS samples (11.61 ± 4.07%). These values describe a change in composition along the sampled waste-management chain but do not isolate the mechanism responsible for that change.

Table 1. Sampling summary from the raw municipal solid waste dataset.

Site	Facility	n	Total mass (kg)	Mean sample mass (kg)	Sample range (kg)
Baldia	GTS	5	512.0	102.4	96.0–105.0
Sharafi	GTS	5	497.0	99.4	96.0–103.0
Truck Stand	GTS	5	476.0	95.2	92.0–99.0
Jam Chakro	LFS	5	503.0	100.6	97.0–103.0
Total	—	20	1988.0	—	92.0–105.0

Note. A separate 0.45-kg e-waste observation was recorded in one sample and was not allocated to the 13 principal categories.

Table 2. Municipal solid waste composition by site, mean ± SD of sample mass fraction (%), with pooled mass fraction.

Component	Baldia	Sharafi	Truck Stand	Jam Chakro	Pooled %
Mixed paper	2.14 ± 0.27	1.24 ± 0.59	2.22 ± 1.07	1.29 ± 0.51	1.71
Newsprint	0.00 ± 0.00	0.18 ± 0.28	0.05 ± 0.10	0.06 ± 0.14	0.07
Corrugated paper/cardboard	0.58 ± 0.21	1.58 ± 0.53	0.26 ± 0.30	0.22 ± 0.20	0.66
Plastic	21.39 ± 4.12	19.20 ± 0.51	21.77 ± 1.58	16.61 ± 4.98	19.71
Food waste	18.04 ± 2.73	12.85 ± 3.42	18.22 ± 5.82	4.72 ± 1.69	13.44
Wood	1.60 ± 0.42	0.59 ± 0.81	0.82 ± 0.42	0.59 ± 0.44	0.90
Other organics/combustibles	8.00 ± 2.11	13.41 ± 3.67	13.41 ± 3.98	13.07 ± 4.21	11.96
Ferrous metals	0.00 ± 0.00	0.06 ± 0.13	0.05 ± 0.09	0.00 ± 0.01	0.03
Aluminium	0.06 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.02
Glass	1.09 ± 1.05	1.11 ± 0.80	0.82 ± 0.75	0.23 ± 0.23	0.81
Other inorganics/non-combustibles	34.43 ± 4.39	32.84 ± 3.35	26.91 ± 4.29	50.54 ± 3.24	36.32
Yard waste	6.30 ± 3.33	10.45 ± 3.61	7.64 ± 3.73	6.24 ± 2.13	7.61
Diapers/sanitary products	6.35 ± 1.74	6.41 ± 0.83	7.84 ± 2.83	6.42 ± 1.71	6.74

Note. Site statistics use n = 5 samples per site. SD = standard deviation. Pooled % uses total component mass divided by total sampled mass.

3.5 Indicative resource-recovery screening

The composition-based grouping placed 35.01% of pooled mass in the potentially combustible screening group, 21.04% in the food-plus-yard group for biological-treatment screening, 0.85% in measured metals and glass, and 43.07% in the residual group (Table 5). The 0.45-kg e-waste observation was outside these groups. The values are therefore best read as a first screening of what warrants further characterization, rather than as a forecast of achievable recovery or diversion.

Table 3. Kruskal-Wallis tests for between-site differences in component mass fractions.

Component	H	p	FDR-adjusted q	q < 0.05
Mixed paper	8.35	0.0393	0.1023	No
Newsprint	2.61	0.4552	0.5366	No
Corrugated paper/cardboard	13.64	0.0034	0.0200	Yes
Plastic	5.63	0.1311	0.2131	No
Food waste	13.01	0.0046	0.0200	Yes
Wood	8.67	0.0340	0.1023	No
Other organics/combustibles	7.11	0.0683	0.1481	No
Ferrous metals	2.39	0.4953	0.5366	No
Aluminium	6.32	0.0972	0.1805	No
Glass	4.48	0.2144	0.3097	No
Other inorganics/non-combustibles	14.15	0.0027	0.0200	Yes
Yard waste	3.90	0.2721	0.3538	No
Diapers/sanitary products	0.69	0.8752	0.8752	No

Note. Benjamini-Hochberg adjustment was applied across the 13 component-wise tests. These are exploratory four-site comparisons, not a general GTS-versus-landfill test.

Table 4. Plastic sub-fractions as percentage of plastic mass, mean ± SD by site and pooled share.

Plastic sub-fraction	Baldia	Sharafi	Truck Stand	Jam Chakro	Pooled %
PET bottles	0.27 ± 0.19	0.16 ± 0.14	0.31 ± 0.45	0.16 ± 0.36	0.22
HDPE bottles	0.05 ± 0.11	2.39 ± 1.68	0.73 ± 1.13	0.18 ± 0.25	0.84
Film plastic	96.96 ± 1.70	93.17 ± 1.49	94.53 ± 1.87	97.24 ± 0.25	95.45
Other plastic	2.72 ± 1.67	4.28 ± 1.19	4.42 ± 0.95	2.42 ± 0.44	3.49

Note. Percentages are relative to plastic mass, not total MSW mass.

Table 5. Indicative composition-based resource-recovery screening.

Screening group	Included physical categories	Pooled mass (%)
Potential combustible / energy-recovery screening	Mixed paper + newsprint + corrugated/cardboard + plastic + wood + other organics/combustibles	35.01
Biological-treatment screening	Food waste + yard waste	21.04
Measured material-recovery screening	Ferrous metals + aluminium + glass	0.85
Residual disposal screening	Other inorganics/non-combustibles + diapers/sanitary products	43.07

Note. Screening groups do not measure treatment yields or recommended process capacities. The 0.45-kg e-waste observation is outside these groups.

4. DISCUSSION

The raw-data reanalysis confirms that the Karachi waste sampled in this study was heterogeneous and that the composition differed appreciably among locations. The pooled profile was dominated by other inorganics/non-combustibles and plastic, while food waste, other organics, yard waste and diapers together formed another substantial share. This pattern is broadly consistent with the wider Karachi literature showing a mixed stream with substantial organic and plastic content while also illustrating by a single City white composition value should be used cautiously. Shahid Airtel 2022 reported seasonal changes in Karachi ways and Hassan at 1226 documented local variability in district east. The present sample level result add evidence that substantial variability also exists among transfer and disposal location within the city.

The higher other inorganic fraction is particularly important this category in the field classification included materials such as Rock sand dirt ceramics plaster and other noncombustible materials it accounted for 436.32% of old mass and exceeded 50% on average Jam Chakro. A high inert fraction reduces the proportion of the waste stream that can be biologically or thermally processor and increases the mass requiring disposal unless inert materials can be separated for a safe beneficial use. The much higher value at Jam Chakro may reflect differences in sources mixing with soil or debris handling at the disposal side or other processes between transfer and final disposal. Because the same load was not tracked the present data set cannot distinguish among these explanations.

Plastic was the second largest food fraction at 19.71%, but the subtraction results are more informative than the total alone approximately 95.5% of the plastic mass was film. PET and HDPE waters were scarce in the mix samples. One plausible explanation is that higher value Richard containers had already been preferentially recovered before the sample ways reached the sorting point whereas lower value flexible film remained. This interpretation is consistent with the documented role of informal recovery in Pakistan (Asim et. al. 2012) and with the material flow evidence for Karachi (Asim et. al., 2022) it should nevertheless be treated as an interpretation rather than a major casual effect. The finding has a practical implication, a recovery strategy focusing only on conventional bottle recycling would address a small portion of the plastic still present in this mixed waste streams; flexible-film collection, contamination control and viable end markets would also be needed.

Food and yard waste together accounted for about 21% of pooled mass in the screening calculation, although food waste varied strongly among sites and was much lower in the Jam Chakro samples. Organic material is commonly considered for composting or anaerobic treatment, but physical mass fraction alone is not sufficient to select a process. Source segregation and contamination are critical, and moisture and biochemical properties influence treatment performance. The Karachi biochemical methane work by Sohoo et al. (2021) demonstrates the value of characterizing waste beyond physical sorting when anaerobic treatment or energy recovery is being considered. The present 21% value should therefore be interpreted as a quantity for further biological-treatment assessment, not as an immediately compostable yield.

The lower mean proportions of plastic, food waste, corrugated/cardboard and glass at Jam Chakro compared with the combined GTS samples initially motivated the original manuscript to discuss scavenging. The raw-data review supports the presence of a compositional difference, but not the original causal wording. Other organics were slightly higher at Jam Chakro, and other inorganics were substantially higher, so it is incorrect to state that every fraction except one declined between GTS and landfill. More importantly, the samples were not paired with waste loads. Informal recovery may contribute to the pattern, especially for saleable materials, but differences in waste origin, residence time, moisture, decomposition, mixing and site handling could also contribute. The revised interpretation is therefore deliberately descriptive.

The statistical reanalysis also changes the strength of the evidence. Earlier graph workbooks contained analyses based on aggregated site means, which do not provide a valid estimate of within-site variation. Using the 20 raw sample records allows variability to be retained. After controlling the false discovery rate across 13 components, only corrugated/cardboard, food waste and other inorganics/non-combustibles showed statistically significant differences among the four sampled sites. Plastic, despite a visually lower mean at Jam Chakro, did not retain statistical significance in the four-site comparison. This distinction between descriptive effect size and statistical evidence is important in a small field dataset.

The composition-based resource-recovery screening also requires careful interpretation. The 35.01% potentially combustible group is not a measured refuse-derived fuel or waste-to-energy feedstock. It includes paper, plastic, wood and other combustible material, but the study did not measure moisture, ash, lower heating value, chlorine, sulphur or other parameters needed for thermal-process design. Siddiqi et al. (2019) and other Pakistan energy studies have used additional physical and energy-related properties to assess waste-to-energy potential. Similarly, Sohoo et al. (2022) showed that disposal and greenhouse-gas management require consideration of landfill conditions, not only incoming composition. The main value of the screening is therefore to identify where additional testing should be directed.

For Karachi waste-management planning, the findings support three practical priorities. First, source segregation should focus on keeping food and yard waste cleaner if biological treatment is to be viable. Second, material-recovery planning should account for the fact that much of the residual plastic is flexible film, while easily saleable rigid containers and metals are present only in small, measured quantities. Third, transfer-station and landfill monitoring should retain sample-level records, dates, source zones and load identifiers. Such records would allow future studies to distinguish seasonal changes from changes occurring during transport and informal recovery and would support a true mass-balance assessment of the system.

The study has several limitations. Exact sampling dates and the temporal coverage of the 20 samples are not documented in the surviving dataset, so seasonal representativeness cannot be demonstrated. Only one landfill/disposal site was sampled, which prevents generalization of a landfill-versus-GTS effect. The transfer-station and landfill samples were not paired loads, so causal attribution to scavenging or transport processes is not possible. Some sub-categories were aggregated according to the original analytical workbook, including Tetra Pak with the corrugated group, and a single e-waste observation was kept outside the 13 principal categories. Finally, the study is a physical characterization only and does not include moisture, proximate/ultimate analysis, calorific value, contaminants, lifecycle performance, economics or market assessment. These limitations define the appropriate use of the results but do not remove the value of the measured sample-level composition.

A strength of the revised analysis is that it returns to the raw 20-sample dataset rather than relying on graph-level means. This makes the sample mass range, within-site SDs, the separate e-waste observation and the multiple-comparison adjustment explicit. For a local field study with modest sample numbers, this transparency is preferable to over-precise inference and provides a clearer basis for replication in a future multi-season campaign.

5. CONCLUSION

Physical characterization of 20 mixed-MSW samples from three Karachi transfer stations and Jam Chakro represented approximately 1,988 kg of waste. The pooled stream contained 36.32% other inorganics/non-combustibles, 19.71% plastic, 13.44% food waste, 11.96% other organics/combustibles, 7.61% yard waste and 6.74% diapers/sanitary products. Film accounted for approximately 95.5% of the measured plastic fraction.

Raw sample-level analysis showed significant differences in corrugated/cardboard, food waste and other inorganics after false-discovery-rate adjustment. Descriptively, Jam Chakro contained less plastic, food waste, corrugated/cardboard and glass than the combined GTS samples, but substantially more other inorganic material. These differences may reflect material recovery and other changes along the management chain, but they cannot be assigned solely to scavenging because the sampled loads were not paired.

The physical composition placed approximately 35% of mass in a potentially combustible screening group, 21% in food and yard material for biological-treatment screening, less than 1% in measured metals and glass, and 43% in residual categories. These are screening proportions, not achievable diversion rates. A stronger next phase should use dated multi-season sampling, paired-load tracking and complementary physical and chemical testing so that recovery and treatment options can be assessed on a technically defensible basis.

DATA AVAILABILITY

The raw data supporting the findings of this study are available from the corresponding author upon reasonable request. The revised analysis was calculated from the original sample-level workbook supplied for this manuscript.

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