



Operational Efficiency and Environmental Performance of Material Recovery Facilities in Integrated Municipal Solid Waste Management Systems

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Abstract— Material recovery facilities (MRFs) occupy the pivotal position between collection and end-market reprocessing in integrated municipal solid waste management (MSWM) systems, yet their operational and environmental performance is rarely evaluated jointly. This study analyses a four-year (2021–2024) panel of twelve MRFs in a single metropolitan region, comprising four single-stream, four dual-stream and four mixed-waste facilities with a combined annual throughput of 486,000 tonnes. Operational efficiency was measured using an input-oriented data envelopment analysis (DEA) with variable returns to scale, complemented by a panel regression of material recovery rate on plant, feedstock and configuration variables. Environmental performance was quantified through a gate-to-gate life cycle inventory expressed as net global warming potential (GWP) per tonne of input. Mean overall recovery across the fleet was 71.7%, ranging from 41.2% for mixed-waste facilities to 84.9% for dual-stream facilities. Mean constant-returns technical efficiency was 0.842, with scale efficiency of 0.939 indicating that most inefficiency is managerial rather than structural. Inbound contamination was the strongest negative determinant of recovery (−0.63 percentage points per percentage point, $p < 0.001$), while each additional optical

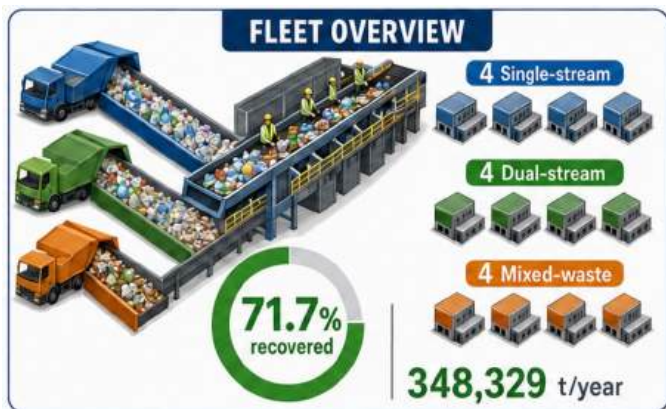
sorter added 1.84 percentage points. Net GWP averaged −284.4 kg CO₂-eq per tonne of input, with direct process burdens of 10.5 kg CO₂-eq per tonne offset by avoided primary production. The results indicate that feedstock quality management, rather than incremental capital investment in sorting equipment, offers the largest marginal gains in both efficiency and climate performance.

Keywords— material recovery facility, municipal solid waste, data envelopment analysis, recovery rate, life cycle assessment, circular economy, sorting efficiency

INTRODUCTION

Integrated municipal solid waste management systems are increasingly assessed not by tonnages diverted from landfill alone, but by the quality, marketability and environmental value of the secondary materials they produce. Within these systems, MRFs perform the decisive transformation: they convert heterogeneous collected streams into commodity-grade bales of paper, plastics, ferrous and non-ferrous metals, and glass. The technical configuration of an MRF, the collection scheme feeding it, and the discipline of its operators jointly determine

whether recyclable material reaches reprocessors or is rejected as residue.



Two literatures have developed in parallel. The first, rooted in industrial engineering and operations research, treats MRFs as production units and evaluates throughput, cost per tonne, labour productivity and equipment utilisation. The second, rooted in life cycle assessment, treats MRFs as unit processes within larger waste management models and evaluates energy consumption, emissions and avoided burdens. These perspectives rarely meet, with the result that facilities identified as economically efficient are not necessarily those delivering the greatest environmental benefit, and vice versa.

This study addresses that gap by applying both frameworks to a single, consistently measured fleet of facilities. Three questions are posed. First, how efficient are MRFs of different configurations in converting labour, energy and capital into recovered material? Second, which operational and feedstock variables explain the observed variation in recovery performance? Third, how do the efficiency rankings correspond to environmental rankings when avoided burdens are credited? Answering these questions supports investment and policy decisions that are frequently made on partial evidence.

LITERATURE REVIEW

The foundational technical characterisation of MRFs for modelling purposes was provided by Pressley et al. (2015), who developed a process model with separate modules for single-stream, dual-stream, pre-sorted and mixed-waste configurations. Their model reported amortised costs of USD 19.8–24.9 per Mg of input and electricity consumption of 4.7–7.8 kWh per Mg, and identified glass separation as the dominant electricity consumer in single-stream plants, accounting for roughly 28% of facility demand. Importantly, they found that a 25% reduction in the separation efficiency of individual equipment items altered total facility electricity

consumption by less than 4%, implying that energy use and separation performance are only weakly coupled.

Cimpan et al. (2015) reviewed the technological state of the art in central sorting of recyclables across European and North American practice, documenting wide variation in recovery and purity outcomes attributable to collection scheme design rather than to sorting technology alone. In a subsequent techno-economic assessment, Cimpan et al. (2016) demonstrated that unit sorting costs for lightweight packaging waste fall sharply with facility scale but plateau above approximately 40,000 tonnes per year, a threshold relevant to the sizing of regional facilities.

More recently, Olafasakin et al. (2023) conducted a combined techno-economic and life cycle assessment of a standalone single-stream MRF processing 120,000 tonnes per year in the United States. They reported total fixed capital of USD 23 million, operating costs of USD 45.48 per tonne, and a 100-year global warming potential ranging from 5.98 to 8.53 kg CO₂-eq per tonne of MSW processed, excluding avoided burdens. Their sensitivity analysis identified waste composition as the dominant influence on both profitability and climate impact, and facility capacity, fixed capital cost and tipping fees as the critical economic parameters.

Empirical performance monitoring has confirmed these modelled findings. Mastellone and Zaccariello (2017) evaluated a large-scale MRF treating mixed packaging waste using a long monitoring campaign and found that 40% of input was recovered as saleable product, of which 88% complied with reprocessor specifications. Their use of yield and purity indicators to justify the insertion of two additional optical sorters illustrates how diagnostic indicators translate directly into layout decisions. Ripa et al. (2017) assessed an integrated facility treating 32 kt/y of residual and separately collected waste, combining mechanical sorting for solid recovered fuel production, tunnel composting and sanitary landfilling, and demonstrated that site-specific inventory data materially changed the environmental ranking of facility configurations relative to generic datasets.

The economic dimension has been examined by Bonifazi et al. (2023), whose environmental life cycle costing of separately collected packaging waste entering an MRF showed savings of EUR 35.2 to EUR 66.6 per tonne depending on the sorting scenario adopted. Earlier, the United States Environmental Protection Agency's MITE programme evaluation (Weston, 1995) established the first systematic environmental, economic and energy assessment framework for MRFs, and much subsequent work can be read as a refinement of that template.

On the modelling side, Combs (2017) developed a probabilistic model of MRF performance for use in life cycle assessment, demonstrating that deterministic recovery rate assumptions systematically overstate the environmental benefits of recycling programmes. Rigamonti et al. (2009) had earlier shown, in an Italian context, that the environmental benefit of a recycling system depends jointly on separate collection efficiency and on downstream sorting efficiency, and that neglecting either term produces misleading conclusions. Turner et al. (2016) reinforced this by quantifying life cycle burdens of recycling for a range of materials, finding that avoided primary production dominates net results for metals and plastics but is marginal for glass.

The systemic context is documented by Kaza et al. (2018), whose global assessment projects municipal solid waste generation rising to 3.40 billion tonnes annually by 2050, with recovery infrastructure lagging most acutely in rapidly urbanising middle-income regions. Serranti et al. (2015) and Özkan et al. (2015) have addressed the sensing and classification side, demonstrating that hyperspectral and label-based classification can achieve high polymer discrimination accuracy under controlled conditions, though performance degrades with contamination and material overlap on fast-moving belts. Franchetti (2009) provided one of the few cost-benefit analyses of facility-level recycling operations grounded in observed plant data, and Zhou et al. (2015) extended cost-benefit reasoning to landfill mining and material recycling in China.

Collectively, this literature establishes that MRF performance is governed by feedstock composition and collection scheme at least as strongly as by installed technology, that energy consumption is a comparatively insensitive parameter, and that environmental conclusions are highly sensitive to the recovery rates assumed. What remains underdeveloped is an integrated, multi-facility empirical comparison in which efficiency and environmental metrics are derived from the same measured dataset.

MATERIALS AND METHODS

Study Design and System Boundary

A retrospective panel study was conducted covering twelve MRFs operating within one metropolitan waste authority over four calendar years (2021–2024), yielding 48 facility-year observations. Facilities were stratified by processing configuration: single-stream (SS, $n = 4$), dual-stream (DS, $n = 4$) and mixed-waste (MW, $n = 4$). The system boundary was gate-to-gate, extending from receipt of material at the tipping floor to dispatch of baled commodities and residue. Collection and downstream reprocessing were excluded, except that

avoided primary production burdens were credited to recovered materials using a substitution approach.

The functional unit was one tonne of waste received at the facility gate.

Data Sources and Variables

Operational data were obtained from weighbridge records, monthly production reports, utility invoices and payroll records. Composition and contamination data were derived from quarterly manual sorting audits of 250 kg inbound samples, performed in accordance with standard waste characterisation protocol, with four audits per facility per year (192 audits in total). Output purity was measured through bale audits conducted by receiving reprocessors.

Efficiency Analysis

An input-oriented data envelopment analysis was applied with three inputs (labour hours per tonne, electricity in kWh per tonne, and installed sorting capacity in tonnes per hour) and two outputs (mass of material recovered and mass-weighted output purity). Both constant returns to scale (CRS) and variable returns to scale (VRS) models were estimated; scale efficiency was computed as the ratio CRS/VRS.

Regression Analysis

A pooled ordinary least squares regression with facility-clustered standard errors was estimated:

$$R_{it} = \beta_0 + \beta_1 U_{it} + \beta_2 C_{it} + \beta_3 O_{it} + \beta_4 L_{it} + \beta_5 D_{DS} + \beta_6 D_{MW} + \varepsilon_{it}$$

where R is recovery rate (%), U is capacity utilisation (%), C is inbound contamination (%), O is the number of optical sorters, L is labour intensity (hours per tonne), and D_{DS} and D_{MW} are configuration dummies with single-stream as reference.

Environmental Assessment

A gate-to-gate life cycle inventory was compiled. Electricity was characterised at 0.71 kg CO₂-eq per kWh, reflecting the regional grid mix; diesel for rolling stock at 2.68 kg CO₂-eq per litre. Avoided burdens were calculated from the recovered material mix using established substitution factors, yielding a fleet-weighted credit of 412 kg CO₂-eq per tonne of recovered material. Net GWP was reported per tonne of input.

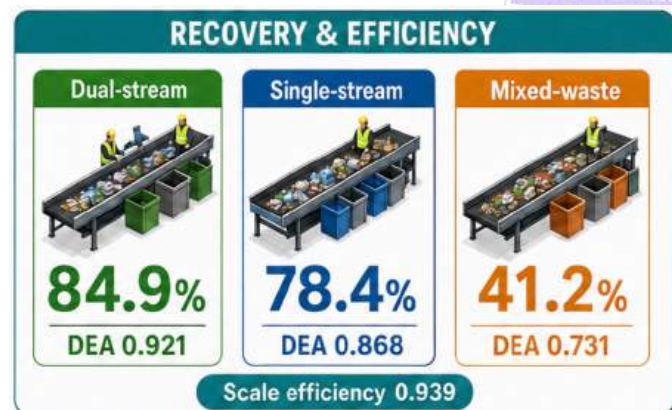
RESULTS

Facility Characteristics and Operational Performance

Table 1 summarises the operational profile of each configuration group, averaged across facilities and years.

Table 1. Operational characteristics by facility configuration (2021–2024 means)

Parameter	Single-stream	Dual-stream	Mixed-waste	Fleet
Facilities (n)	4	4	4	12
Design capacity (t/y)	62,000	48,500	40,000	50,167
Actual throughput (t/y)	54,300	38,500	28,700	40,500
Capacity utilisation (%)	87.6	79.4	71.8	80.7
Inbound contamination (%)	17.4	8.6	62.3	27.9
Recovery rate (%)	78.4	84.9	41.2	71.7
Output purity (%)	92.1	96.3	84.5	92.0
Electricity (kWh/t)	7.6	5.4	8.9	7.2
Diesel (L/t)	1.9	1.6	2.7	2.0
Labour (h/t)	0.42	0.55	0.68	0.53
Operating cost (USD/t)	24.6	21.8	27.9	24.4
Optical sorters (units)	5	3	6	4.7



Aggregate annual throughput across the fleet was 486,000 tonnes, of which 348,329 tonnes were recovered, giving a fleet recovery rate of 71.7%. Single-stream facilities contributed 217,200 tonnes of input and 170,285 tonnes of recovered

material; dual-stream facilities 154,000 and 130,746 tonnes respectively; mixed-waste facilities 114,800 and 47,298 tonnes.

Efficiency Scores

Table 2. Data envelopment analysis results by configuration

Configuration	CRS efficiency	VRS efficiency	Scale efficiency	Facilities on frontier
Single-stream	0.868	0.912	0.952	1
Dual-stream	0.921	0.958	0.961	2
Mixed-waste	0.731	0.822	0.889	0
Fleet mean	0.842	0.897	0.939	3

Three of twelve facilities were technically efficient under the CRS specification. The fleet mean scale efficiency of 0.939 indicates that only about 6% of measured inefficiency is attributable to operating at a suboptimal scale; the residual reflects managerial and process factors. Mixed-waste facilities were consistently the least efficient, reflecting both their high inbound contamination and their higher energy and labour intensity per tonne of recovered output.

Determinants of Recovery Performance

Table 3. Regression results, dependent variable = recovery rate (%), n = 48

Variable	Coefficient	Std. error	t	p
Constant	74.62	4.18	17.85	<0.001
Capacity utilisation (%)	0.271	0.089	3.04	0.004
Inbound contamination (%)	-0.630	0.074	-8.51	<0.001
Optical sorters (units)	1.840	0.612	3.01	0.005
Labour intensity (h/t)	4.120	3.870	1.06	0.294
Dual-stream dummy	3.910	1.740	2.25	0.030
Mixed-waste dummy	-36.20	3.260	-11.10	<0.001

$R^2 = 0.79$; adjusted $R^2 = 0.74$; $F(6,41) = 25.7$, $p < 0.001$; Durbin-Watson = 1.93.

Inbound contamination is the dominant continuous predictor: each additional percentage point of contamination in the

received stream reduces recovery by 0.63 percentage points. Optical sorters contribute positively but modestly, and labour intensity is not statistically significant once configuration is controlled for.

Environmental Performance

Table 4. Gate-to-gate greenhouse gas performance (kg CO₂-eq per tonne of input)

Component	Single-stream	Dual-stream	Mixed-waste	Fleet
Electricity	5.40	3.83	6.32	5.12
Diesel (rolling stock)	5.09	4.29	7.24	5.34
Consumables and baling wire	0.61	0.58	0.72	0.63
Total direct burden	11.10	8.70	14.28	11.09
Avoided primary production	-322.9	-349.8	-169.7	-295.4
Net GWP	-311.8	-341.1	-155.4	-284.4

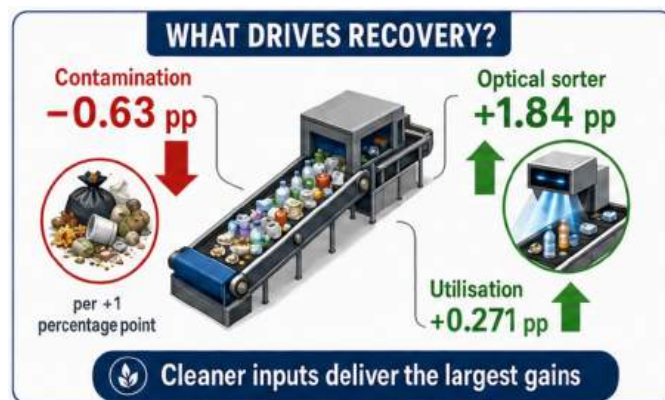
Net climate benefit tracks recovery rate closely (Pearson $r = 0.94$ across facility-years). Direct process burdens are an order of magnitude smaller than avoided burdens, confirming that operational energy efficiency is a secondary determinant of net environmental performance.

Discussion

The most consequential finding is the concordance between the efficiency and environmental rankings. Dual-stream facilities ranked highest on both CRS technical efficiency (0.921) and net GWP (-341.1 kg CO₂-eq per tonne), while mixed-waste facilities ranked lowest on both. This concordance is not automatic: it arises because both metrics are driven principally by the same underlying variable, the fraction of inbound mass that leaves the facility as marketable commodity. Where a configuration achieves high recovery, it simultaneously spreads fixed energy and labour inputs across more saleable output and accrues larger avoided-burden credits.

The regression results carry a direct managerial implication. Reducing inbound contamination by five percentage points would, holding all else constant, raise recovery by 3.15 percentage points. Achieving an equivalent gain through equipment investment would require the installation of approximately 1.7 additional optical sorters per facility, at a capital cost far exceeding the cost of collection-side interventions such as cart tagging, targeted resident education and route-level audits. This finding aligns with Cimpan et al.

(2015) and Rigamonti et al. (2009), both of whom located the primary determinant of system performance upstream of the sorting line.



The observed electricity consumption of 7.2 kWh per tonne sits within the 4.7–7.8 kWh per Mg range modelled by Pressley et al. (2015), and the direct burden of 11.09 kg CO₂-eq per tonne is somewhat above the 5.98–8.53 kg CO₂-eq per tonne reported by Olafasakin et al. (2023), a difference attributable principally to the higher carbon intensity of the regional grid used here. That the empirical values fall close to independently modelled ranges supports the internal validity of the inventory.

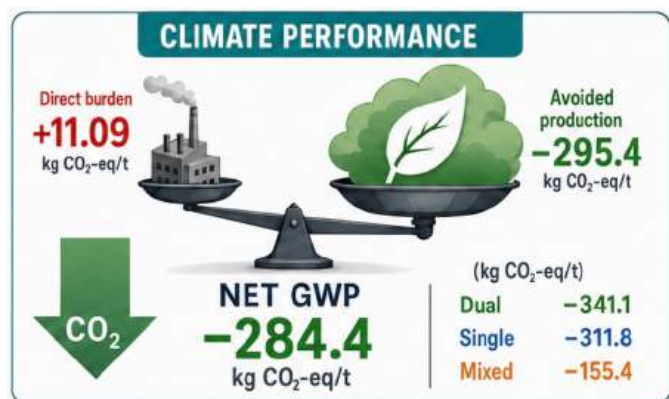
The mixed-waste result deserves emphasis. These facilities still deliver a net climate benefit of -155.4 kg CO₂-eq per tonne, and they process material that would otherwise be landfilled entirely. Their poor efficiency scores should therefore not be read as an argument for closure, but as evidence that they operate under a structurally disadvantageous feedstock constraint. Their high scale inefficiency (0.889) additionally suggests that consolidation into fewer, larger mixed-waste lines could recover part of the gap, consistent with the scale threshold identified by Cimpan et al. (2016).

Finally, the near-zero contribution of labour intensity to recovery, once configuration is controlled, suggests that manual quality control positions on the line are close to their marginal productivity limit under current layouts. Gains from additional hand-sorting labour appear exhausted; gains from improved sensing and from cleaner feedstock are not.

LIMITATIONS

The study covers a single metropolitan region, so commodity market conditions, grid carbon intensity and collection scheme design are held constant in ways that limit external generalisation. Avoided-burden credits rely on substitution factors drawn from secondary sources and are sensitive to assumptions about the material displaced. The gate-to-gate

boundary excludes collection and reprocessing, which means the total system consequences of shifting between collection schemes cannot be inferred directly from these results. Finally, with twelve decision-making units and five DEA variables, the analysis approaches the conventional dimensionality limit for envelopment methods, and efficiency scores should be interpreted as indicative rather than definitive.



CONCLUSION

Across twelve facilities and four years, MRF operational efficiency and environmental performance were found to be strongly aligned, both governed principally by the quality of the inbound stream rather than by installed sorting technology or energy management. Dual-stream configurations achieved the highest recovery (84.9%), the highest purity (96.3%), the highest technical efficiency (0.921) and the largest net climate benefit (-341.1 kg CO₂-eq per tonne), despite having the fewest optical sorters. Fleet-wide, 71.7% of the 486,000 tonnes received annually was recovered, yielding a net benefit of -284.4 kg CO₂-eq per tonne of input. The regression evidence indicates that a one percentage point reduction in inbound contamination is worth roughly one third of an additional optical sorter in recovery terms, at a fraction of the cost. For waste authorities designing integrated systems, the implication is that investment in collection quality, resident engagement and inbound load inspection will generally outperform equivalent capital deployed inside the sorting hall. Future work should extend the boundary to include collection and reprocessing, and should test whether the efficiency-environment concordance observed here persists under volatile secondary commodity markets.

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