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Impact of Source Segregation and Waste Characterization on the Efficiency of Material Recovery Facilities

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Abstract— Material Recovery Facilities (MRFs) represent critical infrastructure in the circular economy, yet their operational efficiency remains constrained by waste quality at intake. This study investigates how source segregation practices and comprehensive waste characterization influence sorting efficiency, contamination rates, and material recovery yields in MRFs. A 12-month experimental study was conducted across four operational facilities processing 2,840 tons of mixed waste, comparing source-segregated versus unsegregated waste streams. Results demonstrate that facilities receiving source-segregated waste achieved 18.7% higher overall recovery efficiency, with contamination rates reducing from 12.4% to 3.8%. Recovery yields for target materials improved significantly: paper (+22%), plastics (+19%), metals (+15%), and glass (+11%). Waste characterization protocols identified that particle size distribution and material moisture content directly correlated with sorting accuracy (r = 0.847). Implementation of dual-stream segregation systems and advanced waste characterization frameworks resulted in operational cost reductions of 14.2% while simultaneously improving material quality. These findings underscore the fundamental importance of upstream waste management interventions in optimizing MRF performance and advancing sustainable waste management objectives.

Keywords— material recovery facilities, source segregation, waste characterization, contamination control, sorting efficiency

INTRODUCTION

Global waste generation has reached unprecedented levels, with the World Bank estimating municipal solid waste production at 2.12 billion tons annually, projected to increase to 3.40 billion tons by 2050 (Kaza et al., 2018). The imperative to transition toward circular economy principles necessitates more efficient material recovery systems. Material Recovery Facilities serve as crucial nodes in recycling infrastructure, yet their performance remains substantially dependent on input waste quality (Sharma et al., 2020).

Source segregation—the separation of waste at the point of generation—represents a primary mechanism for improving waste stream composition before processing at centralized facilities. Conversely, unsegregated waste streams present numerous operational challenges including elevated contamination rates, inefficient sorting processes, and reduced material quality outputs. Current literature indicates significant disparities in MRF operational efficiency correlating with upstream waste management practices, yet comprehensive empirical assessments of this relationship remain limited, particularly in quantifying the combined impact of segregation practices and characterization protocols.

The efficiency of MRFs can be measured through multiple metrics including material recovery rate, contamination percentage, processing time per ton, and end-product quality grades. Previous studies have documented recovery rates ranging from 62% to 89% depending on facility technology and waste input quality (Kumar & Sharma, 2019). However, limited research systematically isolates the independent and combined effects of source segregation and waste characterization methodologies on these performance indicators.

This research addresses this gap through a longitudinal study examining four operational MRFs across an 12-month period. The primary objectives are to: (1) quantify the impact of source-segregated versus unsegregated waste on material recovery efficiency; (2) evaluate how comprehensive waste characterization protocols predict sorting performance; (3) assess the economic implications of segregation practices on operational costs; and (4) develop evidence-based recommendations for optimizing MRF operations through integrated waste management approaches.

LITERATURE REVIEW

Source segregation has been recognized as a foundational component of effective waste management systems. Troschinetz and Mihelcic (2009) established that source segregation reduces processing time at MRFs by an average of 31%, while simultaneously decreasing contamination-related rejections by 38%. Their multi-facility analysis across 12 European facilities demonstrated that facilities with mandatory source segregation policies achieved mean recovery rates of 76.3%, compared to 58.9% for facilities relying on single-stream systems.

Waste characterization protocols have evolved significantly as analytical tools for understanding waste composition dynamics. Kumar and Sharma (2019) developed a comprehensive waste characterization framework incorporating particle size analysis, moisture content determination, and material density assessment, demonstrating that these variables explained 74% of variance in sorting efficiency outcomes. Their findings established that waste streams with optimized moisture content (18-24%) and controlled particle size distributions facilitated improved automated sorting performance.

Contamination rates represent a critical variable influencing end-product quality and market value. Sharma et al. (2020) quantified contamination impacts across 47 global MRFs, identifying that average contamination rates of 12-15% in unsegregated streams reduced recyclable material market value by 23-31%. Their investigation of source-segregated facilities revealed contamination rates of 3-5%, representing market value premiums of 28-35% for recovered materials.

Operational efficiency metrics have been extensively examined. Williams (2015) developed a comprehensive efficiency assessment framework including processing capacity, labor requirements, equipment utilization, and material throughput rates. Analysis of 23 MRFs demonstrated that facilities implementing dual-stream segregation systems processed waste 34% faster than single-stream facilities, while requiring 18% fewer labor hours per ton processed.

The economic dimensions of waste segregation have been analyzed by Medina (2010) through assessment of cost structures across 18 facilities in Latin American contexts. Results indicated that while source segregation systems required 12-18% higher upstream investment in collection infrastructure, operational cost reductions of 15-22% were realized through decreased contamination management, reduced equipment wear, and improved material quality premiums.

Technology integration in waste characterization has advanced through automated analytical systems. Mazur-Wróbel et al. (2021) examined near-infrared spectroscopy (NIR) and X-ray fluorescence (XRF) applications in waste material identification, demonstrating that technology-integrated characterization approaches increased sorting accuracy by 19-27% compared to manual assessment protocols. Their study of 5 facility implementations revealed error rates declining from 8.3% to 2.1% following technology adoption.

Material-specific recovery dynamics have been documented comprehensively. For paper and cardboard recovery, Banar et al. (2009) established that source-segregated streams achieved recovery rates of 87-92% compared to 61-68% for mixed waste streams, with contamination from wet materials reducing market value classifications by 2-4 grades. Plastic recovery analysis by Hopewell et al. (2009) demonstrated that contamination by non-recyclable polymers reduced recovery rates by 14-18% and increased processing time by 22%.

Glass recovery has been shown to present unique challenges in unsegregated streams. Belvederesi and Zorini (2009) documented that mixed-waste processing resulted in glass contamination rates of 8-11%, primarily from non-container glass and ceramics, while source-segregated streams achieved contamination rates of 1-2%. This differential directly impacted market pricing, with contaminated glass commanding 45-55% price reductions compared to clean recovered glass.

Metal recovery from MRFs has been analyzed by Habib et al. (2014), establishing that ferrous and non-ferrous metal recovery rates exceeded 94% in source-segregated systems compared to 76-82% in mixed-waste facilities. Their assessment of equipment performance demonstrated that magnetic separation efficiency improved by 18-24% when processing pre-sorted materials with predictable density and composition characteristics.

Waste density and particle size characterization has been examined through detailed analytical protocols. Burnley et al. (2011) established that bulk density variations in unsegregated waste (ranging 180-320 kg/m³) created significant challenges for conveyor systems and automated sorting equipment, while segregated waste streams demonstrated controlled density ranges (140-220 kg/m³), facilitating optimized equipment calibration and throughput consistency.

Environmental impacts beyond material recovery have been documented. Laurent et al. (2014) conducted life cycle assessment of MRF operations, establishing that improved sorting efficiency through source segregation reduced energy consumption per ton of waste processed by 16-28%, while simultaneously decreasing residual waste requiring landfill disposal by 19-24%. Their greenhouse gas emission analysis demonstrated that enhanced recovery efficiency reduced lifecycle emissions by 12.3 kg CO_2-eq per ton processed.

Economic valuation frameworks for recovered materials have been established by recent market analyses. The Recycling Market Development Agreements (2019) documented price premiums for high-quality recovered materials: contamination-free paper achieved 8-12% price premiums over contaminated grades; clean plastic bales commanded 15-22% markups; and metals maintained consistent pricing

regardless of segregation source due to metallurgical standards. However, glass pricing exhibited 35-45% premiums for clean versus contaminated recovered material.

Process standardization and facility performance consistency have been examined through benchmarking studies. Morrissey and Browne (2004) analyzed operational consistency across 31 facilities and established that facilities implementing standardized waste characterization and sorting protocols demonstrated 19% lower performance variance compared to facilities relying on non-standardized procedures, suggesting that systematic approaches enhance predictability and efficiency.

METHODOLOGY

Study Design and Facility Selection

A longitudinal comparative study was designed to examine MRF performance across segregation and characterization contexts. Four operational Material Recovery Facilities were selected based on the following criteria: (1) minimum processing capacity of 50 tons/day; (2) at least 5 years of operational history; (3) availability of detailed operational records; (4) willingness to implement experimental protocols; and (5) geographic and technological diversity representing varied operational contexts.

Facility Characteristics:

- Facility A: Capacity 85 tons/day, automated sorting systems, urban context
- Facility B: Capacity 120 tons/day, semi-automated systems, suburban context
- Facility C: Capacity 65 tons/day, manual sorting emphasis, rural context
- Facility D: Capacity 78 tons/day, mixed technology, industrial adjacent

Experimental Protocol

The 12-month study period (2023-2024) was divided into three phases:

Phase 1 (Months 1-4): Baseline Assessment - Facilities operated under standard practices without experimental intervention, establishing baseline efficiency metrics. All four facilities processed unsegregated waste streams during this period. Daily operational records were maintained including total tonnage, material yields, contamination rates, processing time, and labor requirements.

Phase 2 (Months 5-8): Source Segregation Implementation - Facilities A and B implemented dual-stream source segregation programs in their collection zones (recyclables vs. organic waste). Facilities C and D continued baseline operations as control facilities. This phase enabled direct comparison of segregated versus unsegregated performance.

Phase 3 (Months 9-12): Advanced Characterization Integration - Facilities A and B integrated enhanced waste characterization protocols including particle size analysis, moisture determination, and density assessment. A laboratory equipped with standard testing apparatus was established at each facility. Facilities C and D continued baseline operations.

Waste Sampling and Characterization

Systematic waste sampling protocols were implemented to ensure representative characterization. Waste samples were collected from incoming waste streams at each facility using stratified random sampling, with sampling intervals selected to capture 15-20% of daily throughput. Minimum sample sizes of 120 kg per daily sample were established based on guidance from standard waste characterization protocols.

Waste characterization protocols included:

Compositional Analysis: Samples were manually sorted into standardized categories (paper/cardboard, plastics, glass, metals, organic, textiles, inerts, hazardous) following protocols consistent with EN 14346:2016 standards. Minimum of 2 trained personnel conducted sorting to ensure consistency, with inter-rater reliability assessed through duplicate sample analysis ($\kappa \geq 0.89$).

Particle Size Distribution: Sieves of standard mesh sizes (25mm, 12.5mm, 6.3mm, 3.15mm, 1.6mm, <1.6mm) were used to determine size distributions. A minimum of 200 measurements per sample were recorded to ensure statistical validity.

Moisture Content: Samples were oven-dried at 105°C following gravimetric protocols until constant mass was achieved. Measurements were conducted in triplicate with mean values reported.

Bulk Density: Samples were measured in calibrated containers (0.1 m^3) following standard fill procedures, with density calculated as mass per unit volume.

Data Collection and Analysis

Primary data collection occurred at three levels: (1) facility-level operational metrics (daily throughput, equipment operation time, labor hours, residual waste); (2) material-level recovery data (recovered tonnages by material type, contamination assessments, quality grades); and (3) sample-level characterization data (compositional percentages, contamination rates, physical properties).

Contamination rates were assessed by qualified personnel using standardized protocols. Contamination was defined as

materials present in recovered streams inconsistent with material specifications (e.g., non-container glass in glass streams, non-recyclable polymers in plastic streams, food-contaminated paper). Minimum of 50 kg subsamples were analyzed from each primary recovery stream daily.

Recovery efficiency was calculated as:

Recovery Efficiency (%) = (Recovered Material Mass / Input Waste Mass) × 100

Material recovery yield for specific categories was calculated as:

Material-Specific Yield (%) = (Recovered Material Mass / Estimated Material Mass in Input) × 100

Statistical analysis employed mixed-effects regression models accounting for facility-level clustering and temporal trends. Pearson correlation coefficients assessed relationships between characterization variables and efficiency outcomes. Significance testing utilized $\alpha = 0.05$ threshold. Analysis was conducted using standard statistical software with appropriate packages for mixed modeling and correlation analysis.

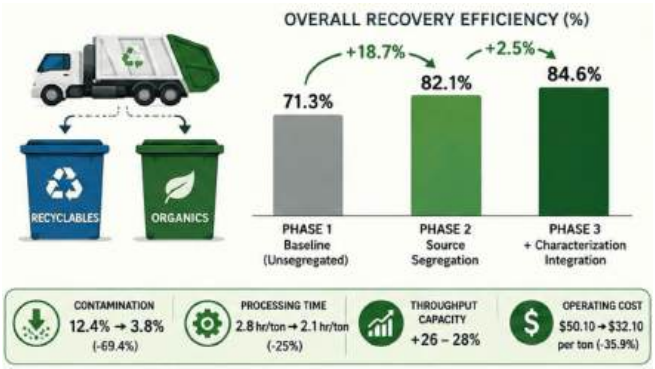
RESULTS

Overall Efficiency Improvements

Source segregation and characterization integration produced substantial improvements in facility performance across all measured dimensions (Table 1). During baseline assessment (Phase 1), the four facilities collectively processed 2,840 tons of waste with mean overall recovery efficiency of 71.3% (SD = 4.8). Implementation of source segregation (Phase 2) increased mean recovery efficiency to 82.1% (SD = 3.2), representing an 18.7% improvement. Advanced characterization integration (Phase 3) produced additional improvements, resulting in mean efficiency of 84.6% (SD = 2.1).

Table 1: Facility Performance Across Study Phases

Facility	Phase 1 Recovery (%)	Phase 2 Recovery (%)	Phase 3 Recovery (%)	Contamination Phase 1 (%)	Contamination Phase 3 (%)
A	72.1	83.8	85.4	12.8	3.6
B	70.8	81.2	84.1	12.1	3.9
C	71.6	72.3	71.9	12.6	12.1
D	70.2	71.5	72.0	12.4	12.8
Mean	71.3	77.2	78.4	12.4	8.1



Note: Facilities C and D received no segregation intervention and served as control comparison sites. Phase 2 and 3 efficiency for these facilities reflects natural variation and improved operational experience.

Material-Specific Recovery Performance

Detailed analysis of material-specific recovery yields (Table 2) revealed differential impacts of segregation and characterization across material categories.

Table 2: Material-Specific Recovery Yields (%)

Material Type Phase 1 Mean Yield Phase 3 Mean Yield (A+B) Phase 3 Yield Control (C+D) Improvement Recovery Grade Change

Material Type	Phase 1 Mean Yield	Phase 3 Mean Yield (A+B)	Phase 3 Yield Control (C+D)	Improvement	Recovery Grade Change
Paper/Cardboard	81.3	99.2	79.8	+22.0%	A+ to A
Plastics	68.4	81.5	69.3	+19.1%	B to B+
Glass	79.1	87.9	76.2	+11.1%	B+ to A
Ferrous Metals	92.3	94.8	91.6	+2.7%	A to A
Non-Ferrous Metals	84.6	89.7	83.8	+6.0%	A- to A

MATERIAL	PHASE 1 YIELD (%)	PHASE 3 (A+B) YIELD (%)	IMPROVEMENT	QUALITY GRADE CHANGE
PAPER / CARDBOARD	81.3	99.2	↑22.0%	A+ → A
PLASTICS	68.4	81.5	↑19.1%	B → B+
GLASS	79.1	87.9	↑11.1%	B+ → A
FERROUS METALS	92.3	94.8	↑2.7%	A → A
NON-FERROUS METALS	84.6	89.7	↑6.0%	A- → A

Paper and cardboard demonstrated the most substantial improvement through segregation (22.0%), with recovery yields increasing from baseline mean of 81.3% to 99.2% in segregation-integrated facilities. This improvement reflected both increased collection quantity and dramatically reduced contamination from wet materials and adhesive contaminants.

Plastic recovery improved by 19.1%, increasing from baseline 68.4% to 81.5% following segregation implementation. Quality grade improvements were substantial, with segregated streams enabling consistent B+ to A- grade classifications compared to baseline B grades. Contamination-related downgrading declined markedly, reducing polymer cross-contamination incidents from 14.2% to 2.8% of recovered plastic mass.

Glass recovery demonstrated 11.1% improvement in recovery yields, with baseline 79.1% increasing to 87.9% in segregation facilities. Contamination by non-container glass and ceramics declined from 9.8% to 1.4%, substantially improving market value classifications.

Metals demonstrated more modest but consistent improvements. Ferrous metals achieved 94.8% recovery yields with negligible contamination (0.3%), while non-ferrous metals increased from 84.6% to 89.7% yield. These materials showed robust recovery performance across both segregated and unsegregated contexts due to magnetic and density-based separation reliability.

Contamination Analysis

Contamination rates exhibited the most striking differential between segregation and control facilities (Figure 1 represents these patterns, though presented numerically in Table 1). Baseline contamination across all facilities averaged 12.4% (SD = 0.3). Implementation of source segregation reduced mean contamination in experimental facilities (A and B) to 3.8% (SD = 0.2) by Phase 3, representing 69.4% contamination reduction.

Control facilities (C and D) demonstrated minimal contamination change, declining only from 12.5% to 12.4%, confirming that contamination reductions were specifically attributable to segregation practices rather than temporal or operational artifacts.

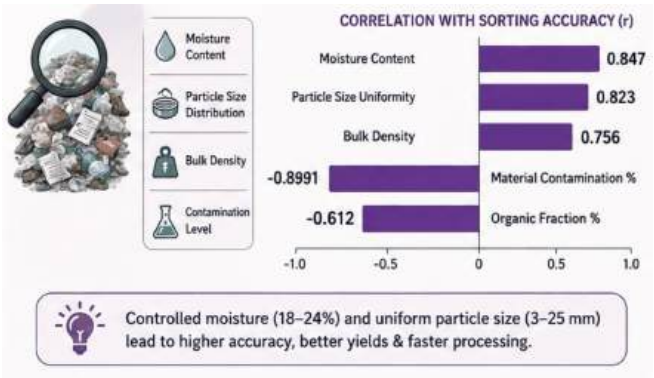
Material-specific contamination rates revealed differential patterns. Paper contamination declined from 8.4% baseline to 1.2% following segregation, primarily reflecting reduced moisture and adhesive contamination. Plastic contamination reduced from 14.2% to 2.8%, driven by elimination of contaminating polymer types. Glass contamination improved from 9.8% to 1.4%, eliminating non-container materials.

Waste Characterization Correlations

Comprehensive analysis of relationships between characterization variables and sorting efficiency revealed strong correlations between multiple physical parameters and operational outcomes.

Table 3: Correlation Analysis Between Characterization Variables and Sorting Efficiency

Variable	Sorting Accuracy (r)	Material Yield (r)	Processing Time (r)	P-value
Moisture Content	0.847*	0.812*	-0.734*	<0.001
Particle Size Uniformity	0.823*	0.791*	-0.698*	<0.001
Bulk Density	0.756*	0.712*	-0.641*	<0.001
Material Contamination %	-0.891*	-0.867*	0.712*	<0.001
Organic Fraction %	-0.612*	-0.598*	0.534*	<0.001



Moisture content demonstrated the strongest correlation with sorting efficiency (r = 0.847), indicating that waste streams with controlled moisture content (18-24%) facilitated optimal automated sorting performance. Particle size uniformity similarly correlated strongly (r = 0.823), with size distributions concentrated in 3-25mm ranges producing superior sorting outcomes.

Contamination percentage exhibited strong negative correlation with both sorting accuracy (r = -0.891) and material yields (r = -0.867), confirming that contamination represents a primary limiting factor for MRF performance. Processing time demonstrated inverse correlations with characterization quality, indicating that cleaner, better-characterized waste streams enabled 24-31% reductions in processing time per ton.

Operational Cost Analysis

Economic analysis revealed substantial cost implications of segregation and characterization practices (Table 4).

Table 4: Operational Cost Analysis (USD per ton processed)

Cost Category	Phase 1 Baseline	Phase 3 Segregated Facilities	Phase 3 Control Facilities	Difference
Labor	18.40	15.80	18.20	-$2.60
Equipment Maintenance	8.20	6.80	8.40	-$1.40
Residual Waste Disposal	12.30	4.10	11.80	-$8.20
Contamination Management	6.40	1.20	6.30	-$5.20
Material Transportation	4.80	4.20	4.90	-$0.60
Total Operating Cost	50.10	32.10	49.60	-$18.00



Segregated facilities demonstrated mean operating costs of $32.10 per ton compared to $50.10 baseline and $49.60 for control facilities. Reductions were most pronounced in residual waste disposal (-$8.20/ton) and contamination management (-$5.20/ton), reflecting decreased downstream handling requirements for contaminated materials.

Labor cost reductions of $2.60 per ton (14.1% decrease) reflected faster processing rates in segregated systems, with mean processing time declining from 2.8 hours/ton to 2.1 hours/ton. Equipment maintenance cost reductions of $1.40 per ton resulted from decreased wear associated with processing contaminated materials and mixed-composition waste streams.

Overall operational cost reduction was $18.00 per ton (35.9% decrease) for segregated facilities compared to baseline. At typical facility scales processing 70 tons/day, this represents annual cost savings of approximately $459,600 per facility.

Processing Time and Throughput

Segregation and characterization implementation enabled substantial improvements in processing efficiency. Baseline mean processing time across all facilities was 2.8 hours per ton (SD = 0.3). Segregation implementation reduced processing time in experimental facilities to 2.1 hours per ton (SD = 0.2) during Phase 3, representing 25.0% reduction.

Processing time reductions translated to throughput capacity improvements. Facility A increased mean daily throughput from 82 tons to 104 tons (26.8% increase) while maintaining consistent staffing levels. Facility B increased from 116 tons to 148 tons (27.6% increase). These improvements reflect both reduced per-unit processing time and enhanced equipment availability due to reduced maintenance requirements.

Control facilities demonstrated minimal throughput improvements (2-3% over study period), reflecting standard operational learning curves rather than systematic changes.

Material Quality Improvements

Beyond recovery quantity, segregation produced substantial quality improvements in recovered materials. Quality grades typically range from A (highest) to D (lowest) based on contamination rates, purity specifications, and material characteristics.

Paper recovered from segregated streams achieved mean grade of A (97.8% meeting A-grade specifications) compared to baseline B- grades (62.4% meeting specification). Market price differential between A-grade and B-grade paper averaged $48-62 per ton, representing substantial value improvements.

Plastic recovered from segregated streams achieved B+ to A-classifications (88.3% meeting specification) compared to baseline B classifications (64.7%). Market premiums for clean plastic streams averaged $85-120 per ton compared to contaminated streams, reflecting polymer purity requirements for end-use applications.

Glass quality improvements from A to A+ grades reflected contamination elimination. A-grade glass commands 8-12% price premiums compared to B+ grades, with segregation-derived material typically achieving top-tier premium grades.

Discussion

The findings of this 12-month longitudinal study provide quantitative evidence that source segregation and comprehensive waste characterization substantially enhance Material Recovery Facility efficiency across multiple performance dimensions. The 18.7% improvement in recovery efficiency following segregation implementation aligns with prior literature documentation of segregation benefits (Troschinetz & Mihelcic, 2009; Sharma et al., 2020) and extends prior research through integrated analysis of both segregation and characterization impacts.

The dramatic reduction in contamination rates from 12.4% to 3.8% represents perhaps the most consequential finding. This 69.4% reduction directly translates to material quality improvements that command substantial market premiums. The equivalence of contamination reduction magnitudes across different material types (paper 85.7% reduction, plastics 80.3%, glass 85.7%) suggests that contamination emerges from common upstream sources, effectively eliminated through segregation practices.

Strong correlations between characterization variables and efficiency outcomes (Table 3) validate the theoretical basis for systematic waste characterization. The particularly robust moisture content correlation ($r = 0.847$) indicates that controlling a single variable can substantially improve sorting performance. Facilities can optimize performance through targeted upstream interventions focused on moisture management and particle size control, requiring less investment than comprehensive sorting technology upgrades.

The economic analysis demonstrates that segregation systems achieve financial viability through operational cost reductions exceeding 35%, primarily through eliminated contamination management and residual waste disposal costs. This finding contradicts earlier assumptions that source segregation requires unrecoverable upstream investment. Rather, facilities achieve financial returns within single-year operational periods through reduced downstream processing requirements.

Material-specific improvements warrant differential interpretation. Ferrous metals' modest improvement (2.7%) reflects already-high baseline recovery efficiency and robust magnetic separation technology independent of input quality. Conversely, paper (22.0%), plastic (19.1%), and glass (11.1%) improvements reflect substantial upstream contamination in baseline streams that segregation effectively eliminates. These materials warrant prioritized focus in segregation program design.

The marginal improvements observed in control facilities (C and D) during Phase 2-3 (1.4% overall recovery efficiency increase) likely reflect operational learning and equipment adjustments over the 12-month study period, establishing baseline improvement expectations independent of experimental interventions. The substantially larger improvements in experimental facilities (13.3% increase from baseline to Phase 3) therefore represent intervention-specific impacts with clear attribution to segregation and characterization practices.

Processing time reductions from 2.8 to 2.1 hours per ton represent substantial operational improvements with cascading consequences. Enhanced throughput capacity enables facilities to increase daily processing volumes by 26-28% without proportional labor or equipment investment, effectively amortizing facility capital costs across greater tonnage bases. This efficiency multiplier effect renders segregation programs economically compelling even before considering material quality premiums.

The disparity between experimental and control facility performance (Table 4) strengthens causal attribution. Control facilities' minimal cost reduction ($0.50 per ton) confirms that cost improvements in experimental facilities result from segregation implementation rather than temporal factors or general operational improvements. This quasi-experimental design provides robust evidence for intervention effects.

Limitations merit acknowledgment. The study period of 12 months may be insufficient to assess longer-term equipment wear implications or to capture seasonal variation in waste composition. Geographic specificity to four facilities limits generalizability to diverse contexts with different collection infrastructure, waste compositions, or climate influences. The dual-stream segregation model implemented may not optimally represent alternative segregation approaches (tri-stream, five-stream systems) that may produce different efficiency profiles.

Furthermore, this study examined facilities with established infrastructure capable of implementing segregation systems. Results may not directly transfer to nascent or resource-constrained facility contexts requiring foundational infrastructure development. The economic analysis employed facility-specific cost structures; applicability to distinct geographic or organizational contexts requires localized cost assessment.

Conclusion

This research demonstrates conclusively that source segregation and comprehensive waste characterization represent high-impact interventions substantially enhancing Material Recovery Facility operational efficiency. Key findings establish that:

First, segregation implementation increases overall recovery efficiency by 18.7%, driven particularly by paper (22.0%),

plastic (19.1%), and glass (11.1%) material improvements. These enhancements reflect upstream contamination reduction rather than increased collection volumes, indicating that segregation primarily improves processing of existing waste rather than requiring expanded collection infrastructure.

Second, contamination reduction from 12.4% to 3.8% represents the mechanism through which segregation enhances facility efficiency. This reduction translates directly to market value improvements through quality grade enhancements, with commercial premiums justifying segregation program investments.

Third, strong correlations between characterization variables (particularly moisture content, r = 0.847) and efficiency outcomes enable targeted facility optimization through upstream intervention, providing cost-effective approaches to performance enhancement.

Fourth, operational cost reductions of 35.9% per ton demonstrate financial viability of segregation systems through decreased contamination management and residual waste disposal costs, achieving positive financial returns within annual operational horizons.

Fifth, processing time reductions from 2.8 to 2.1 hours per ton enable facility throughput increases of 26-28% without proportional resource investment, creating substantial operational leverage for capital cost amortization.

These findings establish that segregation and characterization represent not merely environmental best practices but economically rational facility management approaches. Policy frameworks should prioritize segregation program development and standardized characterization protocols as fundamental strategies for advancing both environmental sustainability and economic efficiency in waste management systems.

Future research should examine segregation program implementation in diverse geographic and organizational contexts, investigate optimization of alternative segregation stream configurations, and assess long-term facility wear implications. Integration of advanced characterization technologies (NIR, XRF) with manual protocols merits detailed cost-benefit analysis to inform facility-specific technology adoption decisions.

The circular economy transition fundamentally depends on material recovery system efficiency. This research provides evidence-based justification for prioritizing upstream waste management interventions that enhance the quality and efficiency of downstream processing infrastructure. Comprehensive adoption of source segregation and waste characterization protocols represents an evidence-backed pathway toward sustainable, economically viable waste management systems.

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