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Evaluation of Sustainable Waste Management: An Analysis of Techno-Economic and Life Cycle Assessments of Municipal Solid Waste Sorting and Decontamination.

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Abstract

This study evaluates the economic and environmental feasibility of Municipal Solid Waste (MSW) sorting and decontamination technologies across urban, suburban, and rural areas. Using Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA), the research assesses cost-effectiveness and environmental impacts, with a focus on cost variability analyzed through Monte Carlo simulations. Findings indicate significant cost differences based on population density: rural areas incur high costs up to $764/ton due to low waste volumes and limited infrastructure, whereas suburban and urban areas have more feasible costs ranging from $36.3 to $142.5/ton. Environmental impacts also vary, with greenhouse gas emissions at 171 kg CO_2 eq/ton for copy paper and 118.6 kg CO_2 eq/ton for plastics. PM2.5 levels are 9.1 g/ton for copy paper and 6.3 g/ton for plastics, with sorting lines being the main contributors. Monte Carlo simulations reveal a 50% probability of costs being below $102.26/ton for copy paper and $115.8/ton for plastics in suburban settings. The study underscores the importance of customized waste management strategies to improve economic viability and sustainability based on local conditions.

1.Introduction

The U.S. recycling industry has faced significant disruptions due to China's import bans on recyclable wastes, particularly under the "National Sword" policy. This policy shift has underscored the need for alternative markets and solutions to address the resulting challenges in the recycling supply chain (Li, 2022).As a response, the U.S. Department of Energy's Bioenergy Technologies Office has allocated funding to develop technologies for converting waste feedstocks into biofuels and biochemicals. These efforts aim to mitigate greenhouse gas emissions and provide sustainable waste management solutions.

Municipal Solid Waste (MSW) is a critical component of waste management discussions, with paper and paperboard being the largest contributors. In 2018, paper and paperboard accounted for 67 million tons of the total 292 million tons of domestic waste generated, representing 23.1% of the waste stream (USEPA, 2020)**.** Despite having the highest recycling rate at 68.2%, significant quantities of paper, especially copy paper, still end up in landfills, leading to substantial economic losses. Approximately $174.58 million is spent annually on landfilling copy paper waste, which comprises around 13.38% of paper waste (USEPA, 2020).

Plastic waste also poses substantial challenges. In 2018, plastic waste generation was 26 million tons, or 12.2% of total waste generation. Plastics are often separated for recycling, but certain types remain non-viable for traditional recycling methods and may be repurposed for alternative uses (USEPA, 2020). Polyethylene Terephthalate (PET) has the highest recycling rate among plastics, but still suffers from significant economic losses, totaling $205 million annually from landfilling.

The environmental and economic impacts of landfilling waste are considerable, exacerbated by contamination issues. Contaminated materials, which include food residues, chemicals, and metals, are often landfilled or incinerated due to the challenges of recycling them effectively (Barraza, 2022). However, these contaminated materials have potential for thermochemical and biochemical conversion processes, which can turn waste paper and plastics into valuable hydrocarbon fuels. Biochemical processes, such as enzymatic hydrolysis and anaerobic digestion, and thermochemical methods, like gasification and pyrolysis, present viable options for waste-to-fuel conversion.

Transforming MSW into fuels introduces several challenges, including the variability in waste compositions, moisture levels, contaminants, and energy content. Efficient sorting and processing infrastructure, supply chain logistics, and waste management regulations are critical to overcoming these hurdles. High sorting and cleaning costs, along with limitations in sorting capacity and efficiency, represent significant barriers. For example, sorting costs alone can account for 30-50% of overall waste management costs (Cimpan et al., 2016).

Decontamination of MSW is essential for effective waste management, involving the removal or reduction of contaminants to ensure environmental safety and resource recovery. This process is crucial for enabling the safe reuse or repurposing of materials, aligning with circular economy principles (Srivastava & Chakma, 2021; Tang et al., 2022). Chemical modifications during decontamination can enhance the performance of biomass for energy production and other applications (Brown et al., 2022; Brown, 2023).

Plastics that are sorted for reuse often carry contaminants, necessitating multiple cleaning steps. These can include both wet and dry cleaning methods. Wet cleaning, involving water or alkaline solutions, is generally more effective but energy-intensive (Lange, 2021; Soto et al., 2020). Dry cleaning methods, such as centrifugation and compressed air, offer some benefits but are less effective at removing all contaminants (Xia & Zhang, 2018). Recent advancements include solvent-based techniques like Dimethyl Ether (DME) and supercritical CO_2, which present eco-friendlier alternatives for cleaning plastic waste while reducing energy consumption (Brown et al., 2022; Liu et al., 2014; Xia & Zhang, 2018).

A range of studies has investigated the environmental and economic dimensions of recycling copy paper. Notable research by Ono et al. (2020) and Hart et al. (2005) underscores the substantial environmental benefits of paper recycling, with Ono specifically highlighting reductions in water usage and greenhouse gas emissions. In contrast, Li et al. (2020) and Hong and Li (2012) offer a more nuanced perspective: Li points to the reduced life cycle costs associated with domestic recycled paper production in China, while Hong emphasizes the environmental advantages of utilizing waste paper for printing and writing applications. Nonetheless, Simion et al. (2017) raise concerns about the significant environmental impacts of recycling processes, particularly in terms of energy consumption and water pollution. Meanwhile, Vukoje (2018) and Bonham (2006) suggest potential solutions, with Vukoje and Rozic (2018) exploring various valorization routes for paper recycling and Bonham assessing the compliance of recycled-fiber-containing copy papers with key standards for durability and longevity.

In the case of TEA, a research into the decontamination of mixed paper and plastics has shown that all techniques achieved a cost target of less than \$30 per dry ton, with plastic decontamination ranging from \$18.16 to \$24.81 per dry ton, indicating the economic viability of certain methods (Brown et al., 2022). Additionally, a TEA of MSW management in Mumbai, India, demonstrated that incineration was the most costly option at \$38 USD per ton due to high capital costs, whereas recycling and sanitary landfill combinations were more economically viable at \$19 USD per ton due to lower operating costs (Sharma & Chandel, 2021). Integrating the insights from TEA and LCA is essential for developing innovative, efficient, and environmentally sound waste management strategies. This approach supports the global shift towards circular economy principles and contributes to advancing the scholarly discourse on sustainable waste management practices.

Examining the economic and environmental aspects of these waste management technologies across different population categories is essential because it reveals how waste generation, composition, and management efficiency vary by setting. In densely populated urban areas, advanced waste processing technologies provide higher waste volumes and better infrastructure. In contrast, rural areas, with lower waste generation and limited infrastructure, can make the implementation of such technologies face unique challenges that. Nevertheless, successfully deploying these technologies in rural settings could yield substantial benefits. For example, establishing waste management facilities in rural areas could create job opportunities, stimulate local economies, and foster regional growth. By adapting waste management strategies to local conditions and addressing the specific challenges faced by different areas, we can optimize resource allocation, enhance sustainability, and support balanced regional development. This approach not only improves waste management efficiency but also promotes economic growth and community resilience in less populated regions.

The purpose of this study is to assess the economic and environmental feasibility of Municipal Solid Waste (MSW) sorting and decontamination technologies across different population categories. By focusing on various demographic settings, including urban, suburban, and rural areas, the study aims to determine how population density and waste generation patterns influence the viability and efficiency of these waste management technologies. To do so, the study will employ Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) to provide a comprehensive evaluation of both cost-effectiveness and environmental impacts. TEA will be used to analyze the economic viability of waste management processes in different population contexts, while LCA will assess their environmental footprint.

Additionally, the study will also explore the variability in costs and economic performance through Monte Carlo simulations. This approach will allow for a more nuanced understanding of the financial implications and risk factors associated with implementing sorting and decontamination technologies in diverse population settings. By incorporating these analyses, the study aims to offer insights into optimizing waste management practices, enhancing resource recovery, and promoting sustainable solutions tailored to specific population categories.

2.Methodology

This research employs a comprehensive methodology to evaluate the techno-economic and environmental aspects of integrating sorting lines and decontamination processes for Municipal Solid Waste (MSW) across rural, suburban, and urban areas. The study assumes MSW is processed in a Material Recovery Facility (MRF) with a sorting line recovering 65% of waste fractions, which then undergoes decontamination.

The techno-economic assessment involves data collection from experiments, modeled using Aspen Plus, and economic analysis via Aspen Economic Analyzer. It includes capital investment, operational costs, and revenue streams for each population category, with specific financial metrics like total cost per ton of recovered products such as copy paper and plastics.

The environmental assessment quantifies greenhouse gas emissions and air pollutants by using life cycle assessments (LCAs) to analyze impacts like Greenhouse Gas emissions and $PM_{2.5}$. The study defines four population categories (rural, suburban 1, suburban 2, and urban) based on population size, and compares costs, benefits, and environmental impacts across these categories. A named city is defined as a rural area if the number of populations is greater than 1000,000 people. Similarly, for cities with population greater than 500,000 and 50,000 people is termed as sub-urban1 and sub-urban2 respectively. Cities with populations greater than 5,000 are termed as urban. By considering factors like population density, waste composition, and infrastructure, the research aims to inform waste management policies and practices through detailed economic and environmental analysis.

2.1 Process Description

This section will describe the process assumed for each step, including the sorting and decontamination of each material.

The study's sorting line is based on the VecoPlan MSW sorting process. This process includes shredding, magnets for ferrous separation, screening, air classification, eddy currents for non-ferrous separation, and near-infrared detection for plastic recovery, all utilizing simulations from previous studies. The decontamination model follows experimental procedures from the Idaho National Laboratory.

For copy paper, the decontamination involves a reactor with an H_2SO_4 solution, followed by solid filtration and water washes. This process separates the final product into solids and a neutralized solution, adhering to the experimental parameters outlined in studies by Brown (2023) and Brown et al. (2022). The goal of this process is to modify ash and lignin content to enhance performance.

For plastics, the decontamination process is based on the study by Lee et al. (2023). This technology removes physical contaminants using Dimethyl Ether (DME) as a solvent. Plastics are introduced into an extraction column containing liquefied DME, and the system recovers about 99% of the solvent through mechanical vapor compression. This process effectively removes approximately 90% of contaminants.

2.2 Technoeconomic Assessment

In this study, the methodology for estimating the total cost of Municipal Solid Waste (MSW) sorting and decontamination technologies is anchored in a comprehensive economic analysis framework. The process begins with identifying and categorizing all relevant cost elements, including capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX covers the upfront costs for equipment and infrastructure, while OPEX addresses ongoing expenses such as labor, maintenance, and utilities. Integrating these costs into a financial model allows for a detailed calculation of the total cost over the project's lifecycle.

This section critically evaluates the economic feasibility of the MSW sorting and decontamination processes by calculating the total cost per material of interest, based on CAPEX and OPEX. Cost data for the sorting line were sourced from internal studies conducted by Idaho National Laboratory, while details for each decontamination process were obtained from the Aspen Economic Analyzer. By combining this data with the financial assumptions outlined in Table 1, a comprehensive total cost assessment for each product was developed. All these assumption are referred to previous studies (Brown et al., 2022; Lee et al., 2023). This approach is crucial for determining the economic viability of the technologies and informing investment decisions, ensuring that the proposed solutions are both cost-effective and practical.

Table 1. Financial Assumptions

Inputs	Value
Inflation Rate	2%
Utility Fuel Used	Natural Gas
Natural Gas Cost ($/MMBtu)	7.55

Interest Rate	8%
Maintenance for machine	1%
Insurance	1%
Salvage rate	15%
Labor Cost ($/h)	33
Installation Assumption (35%)	35%

2.3 Life Cycle Assessment

The Life Cycle Assessment (LCA) framework for evaluating greenhouse gas (GHG) emissions and particulate matter (PM2.5) consists of four key phases. First, the goal and scope definition phase establishes the study's purpose, such as assessing the environmental impacts of a specific product, while defining the system boundaries from raw material extraction to end-of-life disposal. Next, the inventory analysis phase compiles a comprehensive inventory to quantify energy inputs, material flows, and emissions associated with each stage, ensuring reliable data sources. In the impact assessment phase, the inventory data is analyzed to quantify GHG emissions (in CO_2 equivalents) and $PM_{2.5}$ emissions (in mass) using established methodologies. The final interpretation phase identifies emissions hotspots and draws conclusions about overall environmental performance, supporting informed decision-making to enhance sustainability.

In evaluating the environmental impacts, a life-cycle inventory was conducted according to ISO 14040 for a gate-to-gate system of the sorting and decontamination process for specific materials (Finkbeiner et al., 2006). The functional unit was defined as one ton of copy paper and one ton of plastic separated from the sorting line. Two emissions were analyzed: GHG emissions and PM2.5. The assessment utilized data from the GREET database, yielding key outcomes in terms of GHG and PM2.5 emissions per ton of each material.

2.4 Uncertainty Analysis

Uncertainty analysis was performed using Monte Carlo simulation to evaluate the variability in the generation and composition of municipal solid waste (MSW) across different population categories. This approach aims to provide a more realistic estimate of the costs involved.

To conduct this analysis, we used XLRisk software and incorporated probability distributions for selected input parameters, including population size, waste generation, and MSW composition. The variability of each parameter was modeled using a triangular distribution with a ±25% range for key variables that could impact the final cost, such as population size, MSW generation rates, and initial MSW composition.

The primary outcome of this analysis is the probability distribution and cumulative probability of the total system cost for processing plastics and copy paper.

3. Results and Discussion

3.1 Technoeconomic Assessment

Integrating Municipal Solid Waste (MSW) composition analysis with the recovery of specific portions for decontamination preprocessing offers a strategic approach to waste management. This study evaluates the feasibility of this integration through a Techno-Economic Assessment (TEA) of sorting and decontamination processes for two MSW fractions: copy paper and plastic (PET). The total costs for each population scenario, depicted in Figure 1, are expressed in 2016 USD. The figure highlights the main cost contributors across four population categories.

The key findings are:

- **Rural Areas:** Integrating sorting and decontamination lines is economically challenging, with costs around $764 per ton. Low population density results in insufficient waste generation to justify the investment, leading to underutilization of infrastructure.
- **Suburban Areas (Category 1 and Higher):** The integration of sorting and decontamination systems proves more feasible, with costs ranging from $36.3 to $142.5 per ton. Higher population densities and waste volumes in these areas support the investment, making future implementation viable.
- **General Trends:** Sorting lines incur higher costs compared to decontamination processes. The feasibility of these systems is significantly influenced by population size, affecting waste generation rates and the efficiency of sorting and processing operations.

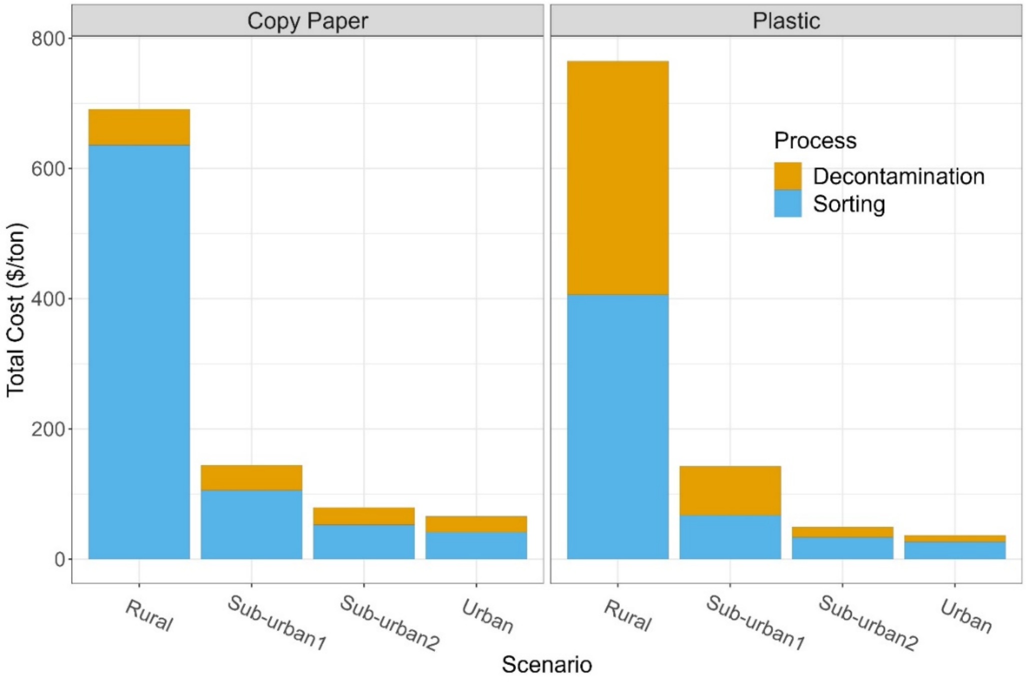


Figure 1. Total cost of each population category for processing copy paper and plastic

The feasibility of implementing a sorting line and decontamination process in a Material Recovery Facility (MRF) for MSW is closely tied to the population size served by the facility, as depicted in Figure 1. The number of people in each area profoundly impacts waste generation rates, influencing the volume and composition of the waste stream. Smaller populations may face deficiencies in both MSW generation and recovery for decontamination processing. Conversely, an increasing population often leads to growing waste quantities, enabling consistent sorting operations and higher throughput for decontamination technology.

However, integrating a sorting line with municipal solid waste (MSW) preprocessing in rural areas presents a challenge that may render the high-cost solution. The sparse population density characteristic of rural regions may result in insufficient total waste generation and the desired fraction to sustain the operations of a sorting line and preprocessing facility. The lower volume of MSW collected in rural areas compared to urban counterparts could lead to underutilization of the infrastructure, making it economically unviable. Additionally, as small useful fraction interested in the decontamination process results in an increase of the entire cost. While integrating a sorting line with MSW preprocessing holds potential for improving waste management practices, the unique characteristics of rural areas, including low population density, and limited labor resources, may render the solution infeasible or economically unviable in practice.

Contrary to suburban and urban areas, the integration of a sorting line with MSW preprocessing system presents more feasible solutions due to several factors. Firstly, these areas typically have higher population densities and, consequently, generate larger volumes of waste. This higher waste generation can justify the investment in sorting and preprocessing facilities by ensuring a steady supply of materials for processing. Furthermore, suburban and urban areas often have access to a skilled workforce, technical expertise, and robust utilities infrastructure, which are essential for the successful operation of sorting lines and preprocessing equipment. The presence of these resources enables efficient operations and maintenance of waste management facilities, enhancing overall effectiveness and sustainability. Overall, the combination of higher waste volumes and robust infrastructure makes integrating sorting and preprocessing facilities with MSW management strategies more feasible in suburban and urban areas. By leveraging these advantages, communities can improve waste diversion efforts, enhance recycling rates, and mitigate environmental impacts associated with waste disposal.

Additionally, variability in waste composition linked to population size is another crucial factor affecting the financial assessment. Different demographic groups contribute diverse types and amounts of waste, translating into higher recovery and throughput for the next process. By analyzing the waste stream, waste management facilities can identify materials that are valuable for the next step, streamlining the recovery process and optimizing decontamination preprocessing steps for specific material challenges.

On the other hand, a key aspect of feasibility lies in the targeted recovery based on MSW composition. By analyzing the waste stream, waste management facilities can identify materials that are valuable for the next step. This targeted recovery for this study, such as isolating copy paper and plastics known for their contamination potential, not only streamlines the overall recovery process but also ensures that the subsequent decontamination preprocessing steps are optimized for specific challenges posed by the materials.

By analyzing the entire process in Figure 1, the sorting line represents the higher cost for the entire process most evident in the rural case. The lower throughput generated in the area and the multiple sorting steps to recover only a small fraction of usable fraction compared to the initial MSW processed are the main reason for the final cost. Therefore, for this case some improvements in sorting design to recover the desired fractions at earlier stages and increase the proportion of usable fractions would generate a more feasible result.

On the other hand, optimized decontamination preprocessing is a critical element in determining feasibility. The recovered materials designated for decontamination undergo specialized treatment processes to remove contaminants effectively. Feasibility is evident in the strategic focus on materials with high contamination potential, ensuring that the decontamination process is both efficient and targeted. This approach contributes to the feasibility of the waste recovery system by maximizing the effectiveness of the decontamination phase. Furthermore, the alignment with circular economy principles enhances the feasibility of the integrated approach. The recovered materials, now decontaminated and of higher quality, can be reintroduced into the production cycle. This circular system reduces the demand for virgin resources, aligning with sustainable practices and contributing to long-term environmental and economic feasibility.

The study's novelty lies in its detailed examination of how population density impacts the feasibility of waste management technologies, providing a fresh perspective on optimizing these processes across various demographic settings. By analyzing the economic and environmental impacts of sorting and decontamination, and how variability in waste composition affects financial assessments, the research offers new insights into enhancing efficiency through targeted material recovery. It emphasizes the importance of optimizing sorting and preprocessing designs to manage materials with high contamination potential effectively. The study highlights that integrating these processes in suburban and densely populated areas presents a practical approach, improving resource recovery and supporting sustainability efforts. In conclusion, the population size served by a Material Recovery Facility is crucial for determining the feasibility of sorting and decontamination processes for Municipal Solid Waste (MSW). Understanding waste generation patterns and composition variability is essential for designing and maintaining effective waste management systems. The study also suggests that improving sorting designs and aligning MSW composition with targeted recovery can enhance waste recovery processes, particularly in rural areas, thereby contributing to more sustainable and efficient waste management.

3.2 Environmental Assessment of the MSW Decontamination Process

The greenhouse gas (GHG) emissions and PM2.5 levels for various population categories and the entire integration process between the sorting line and decontamination of copy paper and plastic are outlined in Table 2. Two main factors drive each environmental impact:

- The process applied for copy paper results in higher GHG emissions, totaling 171 kg CO_2 eq/ton, compared to plastic, which has emissions of 118.5 kg CO_2 eq/ton.
- Similarly, the entire system for copy paper produces more PM $_{2.5}$ emissions, with 9.1 g $PM_{2.5}$/ton, whereas plastic has a total of 6.3 g $PM_{2.5}$/ton.
- When comparing the individual processes, the sorting line shows higher emissions for copy paper than for plastic, while the decontamination step has higher emissions for plastic than for copy paper.
- In both processes, the sorting line is the primary contributor to these emissions.

Table 2. Environmental Impact of the MSW sorting and decontamination process

	Copy Paper		**Plastic**	
	kgCO_2 eq/ton	g$PM_{2.5}$ eq/ton	kgCO_2 eq/ton	g$PM_{2.5}$ eq/ton
Sorting	166.8	8.8	106.5	5.6
Decontamination	4.2	0.2	12.1	0.6
Total	**171**	**9.1**	**118.6**	**6.3**

The findings highlight several key points regarding the environmental impact of processing copy paper compared to plastic. When examining the individual processes, the sorting line exhibits higher emissions for copy paper than for plastic, while the decontamination step shows greater emissions for plastic. Notably, in both processes, the sorting line is the primary contributor to overall emissions.

Several factors explain these findings. Firstly, the sorting line emits similar levels across both processes, but the recovery fraction for copy paper is lower than that for plastic, resulting in higher emissions per ton for copy paper. Secondly, the decontamination process for plastic operates under more extreme conditions, including higher temperatures and pressures, compared to the more benign conditions for copy paper. This contributes to higher emissions per ton for plastic.

However, when considering the entire system, copy paper results in significantly higher greenhouse gas (GHG) emissions and $PM_{2.5}$ compared to plastic, which emits considerably lower amounts. This disparity highlights that the environmental footprint of copy paper is more substantial.

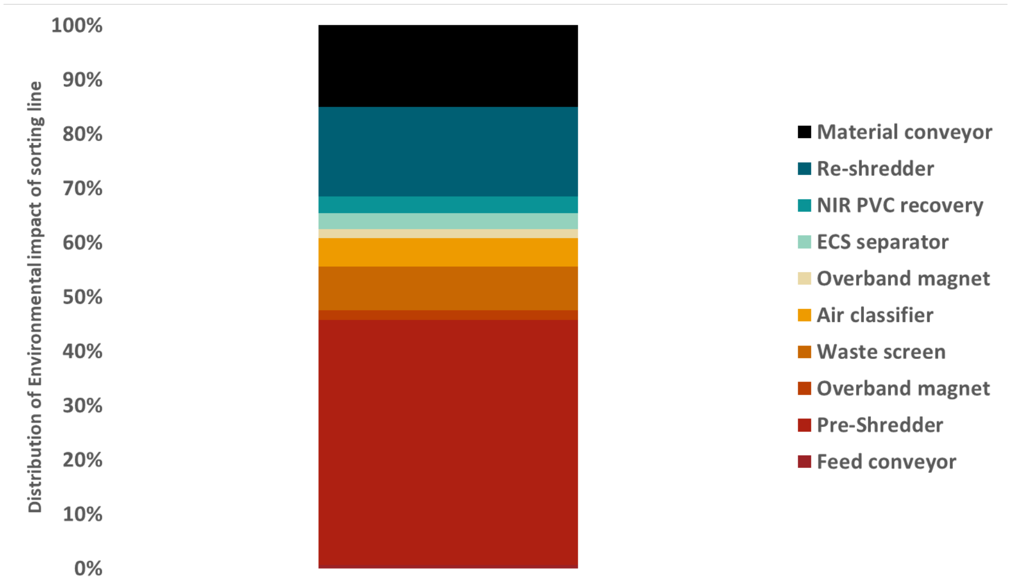
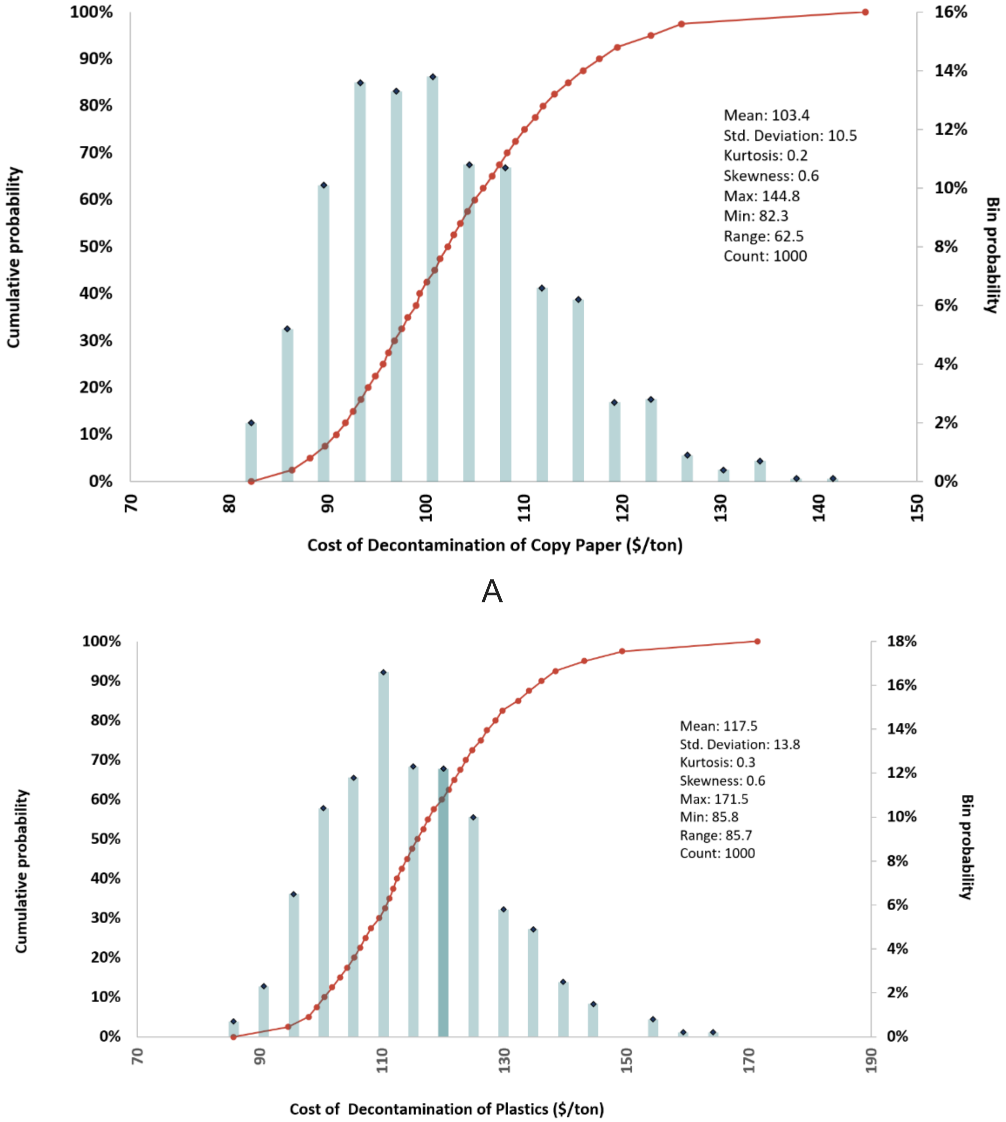


Figure 2 Emission Distribution in the Sorting Line

Additionally, within the sorting line, the pre-shredder machine contributes significantly to emissions due to the variability in moisture content of municipal solid waste (MSW), making this step highly energy-intensive, as illustrated in Figure 2. Finally, emissions tend to increase with throughput, particularly in urban areas where larger volumes of waste are processed. This can lead to higher energy consumption and raw material usage, resulting in an estimated 10% increase in emissions from rural to urban settings.

In the context of economic evaluation, it is essential to assess environmental considerations to understand the trade-offs associated with the MSW decontamination and sorting processes. This evaluation presents an opportunity to reduce landfill space, which not only minimizes costs and emissions but also allows for the exploration of alternative uses for MSW. By prioritizing these environmental aspects, we can make more informed decisions that benefit both the economy and the environment.

3.3 Uncertainty Analysis



A

B

Figure 3. Probability and cumulative distribution of the total system cost suburban-1 category. A. Copy Paper. B. Plastic.

Studying variability in waste composition and generation using Monte Carlo simulation is crucial for optimizing Municipal Solid Waste (MSW) sorting and decontamination processes. This simulation offers a quantitative approach to assessing the risks and financial impacts associated with varying waste streams. By running numerous simulations with different waste composition scenarios, it generates a range of cost estimates and performance outcomes, which enhances the accuracy of financial planning and budgeting for waste management facilities. This approach allows for detailed scenario analysis, providing insights into how diverse waste types and contamination levels affect operational efficiency.

For instance, in the suburban case, Monte Carlo simulations estimate that the manufacturing costs range from USD 82.26 to 144.80 per ton for copy paper and USD 85.80 to 171.52 per ton for plastic. The results indicate approximately a 50% probability that the total cost will be lower than the deterministic values of USD 102.26 per ton for copy paper and USD 115.80 per ton for plastic. These simulations not only provide valuable quantitative information but also highlight potential opportunities for achieving feasible solutions within this population category. They support informed decision-making and strategic planning by identifying areas where waste management strategies can be adapted to varying conditions, thus enhancing resource recovery and ensuring regulatory compliance. Ultimately, Monte Carlo simulations enable more efficient and effective waste management practices by addressing the inherent variability in waste composition and generation. The uncertainty analysis for other cases is presented in the supplementary material.

The study's limitations include the reliance on yearly data to assess municipal solid waste (MSW) composition, which might oversimplify waste generation patterns and overlook seasonal variations. Additionally, using a factor-based approach for job creation may not accurately reflect the complexities between waste management practices and employment opportunities. To address these issues, future research should use more frequent and detailed data collection methods for a better understanding of MSW dynamics and job creation accuracy. In rural areas, the study found that inadequate sorting design led to infeasible solutions, highlighting the need for improved sorting techniques to recover desired material fractions earlier. This improvement is essential for effective waste management in rural settings. Future research should focus on refining these techniques to enhance efficiency and evaluating the suitability of other paper fractions to improve waste recovery and resource utilization.

4. Conclusion.

This study underscores the critical influence of population size on the feasibility of implementing sorting and decontamination processes in Material Recovery Facilities (MRFs) for municipal solid waste (MSW). Our analysis reveals that higher population densities, characteristic of urban and suburban areas, lead to increased waste generation, thereby justifying the investment in advanced waste management technologies. In contrast, rural areas face significant challenges due to lower population densities, which often result in insufficient waste volumes to sustain economically viable sorting and preprocessing operations.

The variability in waste composition, driven by demographic factors, plays a vital role in financial assessments of waste management systems. By strategically focusing on the recovery of materials with high contamination potential, such as copy paper and plastics, facilities can optimize decontamination processes, enhance recovery efficiency, and align with circular economy principles. This targeted approach not only maximizes the effectiveness of decontamination but also facilitates the reintegration of recovered materials into production cycles, ultimately contributing to sustainability goals.

Furthermore, this research highlights the importance of integrating economic evaluations with environmental considerations. By understanding the trade-offs associated with MSW processing, stakeholders can make informed decisions that minimize landfill usage and associated costs while maximizing resource recovery. The use of Monte Carlo simulations has proven invaluable in assessing risks and financial impacts, allowing for a comprehensive understanding of the variability in waste streams.

While the findings provide valuable insights, the study acknowledges limitations, such as the reliance on yearly data that may overlook seasonal fluctuations in waste generation. Future research should aim to incorporate more detailed, frequent data collection to better capture the dynamics of MSW and its implications for job creation and resource utilization.

In conclusion, optimizing sorting designs, particularly in rural areas, and aligning waste composition with targeted recovery strategies are essential for improving the feasibility and sustainability of waste management practices. By leveraging the advantages offered by higher population densities and robust infrastructure in urban and suburban settings, communities can enhance their waste diversion efforts, support recycling initiatives, and mitigate the environmental impacts associated with waste disposal.

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CRediT authorship contribution statement

Maria A Herrera Diaz: Conceptualization, Methodology, Writing –original draft, Writing – review & editing. **Yingqian Lin:** Conceptualization, Writing –original draft, Writing – review & editing. **Pralhad H. Burli:** Conceptualization, Writing –original draft, Writing – review & editing. **Tasmin Hossain:** Conceptualization, Writing –original draft, Writing – review & editing. **Damon S. Hartley**: Conceptualization. **Vicki S. Thompson:** Conceptualization.

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