

Why are recyclable material recovery facilities not economically self-sustaining? A technical, financial and social analysis based on data from units in Brazil

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Abstract

This study assesses operational and financial performance, as well as social and labour aspects, of 12 material recovery facilities (MRFs) in 4 Brazilian regions, using monthly data from 2024. An analytical framework consisting of 13 metrics was developed to evaluate productivity, costs, revenue and labour indicators. Statistical analyses were conducted to explore the relationships between these metrics and their effects on MRF outcomes. Results reveal significant variability in productivity across facilities, with a negative correlation between processing costs and productivity, but no direct link to revenue generation, suggesting external market influences. Rejection rates ranged from 10.07% to 42.38%, with moderate effects on productivity. The cost per mass processed varied significantly, from 11.13 to 41.08 USD tonne⁻¹, with an average of 23.63 USD tonne⁻¹. Financially, only two MRFs achieved over 70% self-sufficiency, with most relying on external subsidies. Labour costs dominated operational expenses. Worker turnover ranged from 17% to 81%, negatively impacting costs and efficiency. The study also explores revenue models and their influence on operations and concludes that MRF sustainability requires not only operational improvements but also innovative financing models, including service fees, public-private partnerships and extended producer responsibility mechanisms. Policies addressing technical efficiency, social equity and revenue stability are crucial for strengthening MRFs. The findings offer insights for similar contexts in developing countries, and the metrics and indicators proposed can be viewed as operational key performance indicators that can be applied globally to assess MRF performance in diverse settings, offering a valuable tool for future studies and standardising performance evaluation.

Keywords

Recycling, material recovery facility, waste pickers cooperatives, municipal solid waste, technical and economic analysis, work conditions

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Introduction

The linear economic model has proven to be unsustainable in the face of the depletion of natural resources and the increase in solid waste generation. According to data from the United Nations Environment Programme, global municipal solid waste production, which reached 2.1 billion tonnes in 2023, is projected to reach 3.8 billion tonnes by 2050 (UNEP and ISWA, 2024). In this context, strategies such as reuse, recycling and material recovery emerge as fundamental pillars for the transition towards a circular economy, capable of promoting environmental and economic sustainability (Badran et al., 2025; Bongers and Casas, 2022).

However, effective recycling development depends on a complex supply chain involving multiple processes and actors. In many countries in the Global South, this chain includes waste

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pickers, who play a crucial role in the waste management system. In Brazil, for example, 8.3% of urban solid waste generated in 2023 reached the recycling chain – 32.8% through formal systems and 67.2% by informal waste pickers (ABREMA, 2024). Under this framework, recyclable material recovery facilities (MRFs) belong to the formal recycling system. In Brazil, waste picker associations are primarily responsible for the door-to-door collection, transportation, sorting and pre-processing of recyclable materials. These associations have organised themselves and established partnerships with municipal selective collection programmes, while also operating independently of public authorities (Lima et al., 2024; Silva de Souza Lima and Mancini, 2017).

Despite the importance of these associations, especially in small municipalities, the main obstacle identified is financial constraints. Other difficulties include the lack of clear strategies in public policies, the low level of public education on waste and the obsolescence and inadequacy of operational equipment (Deus et al., 2022).

The lack of adequate infrastructure and machinery in a MRF significantly compromises essential stages of the process, such as sorting, blending and bundling of materials. This deficiency is among the main factors that reduce the efficiency of the recycling market, resulting in a decrease in the added value of waste due to the low quality of processed materials and higher reject rates (Siman et al., 2020). A study conducted by Moura et al. (2018) at the main recycling cooperative in Blumenau, Brazil, revealed that 30.5% of the total sorted waste was classified as reject. This scenario is exacerbated by factors such as recyclable materials, difficulties in efficient waste segregation and challenges in marketing certain materials with recycling potential. To reverse this situation, it is essential to reduce contamination in the recycling stream, improve the efficiency of the processing system and strengthen economic markets for recycled materials (de Almeida et al., 2021).

The primary source of income for waste pickers is directly related to the value chain of recyclable waste. However, the financial sustainability of this activity is compromised by the absence of municipal legislation ensuring payment for the collection and sorting services provided by these workers (Calderón Márquez et al., 2021). According to the National Association of Recyclable Materials Collectors (ANCAT), the average income of waste pickers associated with recycling cooperatives in Brazil is BRL 1372.52, or USD 240.79 at the current exchange rate (BRL 5.70=USD 1.00), which is less than the current minimum wage of BRL 1412 (USD 247.72; Pragma, 2023). A study conducted with 300 informal waste pickers in Brazil revealed that 70% of them earn up to BRL 1099 per month (USD 192.81; CEMPRE, 2023). Therefore, the economic viability of waste pickers depends on the implementation of public policies that formalize and enhance their role in solid waste.

Considering that MRFs are crucial for integrated waste management, as they reduce the demand for virgin resources, promote a circular economy and extend landfill lifespan through

waste minimization, it is important to assess their performance across multiple dimensions. This study evaluates 12 MRFs located in medium-sized municipalities across 4 Brazilian regions, using monthly operational data from 2024. An analytical framework consisting of 13 metrics was developed to assess operational and financial performance, as well as social and labour aspects. By applying statistical analyses, we examine the relationships between these metrics and their impact on MRF performance. Additionally, the study explores the revenue models necessary to ensure financial sustainability and fair compensation for workers, and how these models influence facility operations.

Brazil, with its socio-economic characteristics and waste management challenges, shares similarities with other developing countries and those in the Global South, making the findings of this study relevant beyond its immediate context. Furthermore, the metrics and indicators proposed and calculated in this research can be viewed as operational key performance indicators, which can be applied by other researchers to assess MRF performance in different settings. This approach provides a valuable tool for future studies and helps standardise performance evaluation across various regions and contexts. This research contributes to the field by analysing a larger number of geographically diverse facilities in a continental-sized country and applying a rigorous statistical approach to evaluate MRF performance.

Methods

The data set, provided by Instituto Recicleiros, a civil society organisation focused on developing municipal recycling programmes, includes monthly records from 12 MRFs located in municipalities across 4 Brazilian regions (Figure 1). These municipalities were selected through open calls issued by Instituto Recicleiros, with urban populations ranging from 32,500 to 200,000 inhabitants. Additional demographic details on these municipalities are provided in the Supplemental Material.

The data set provides detailed financial and operational records for the base year of 2024, such as costs (e.g. labour, administrative expenses, operational expenditures and taxes), revenues from material sales, workforce composition and turnover rates.

Although geographically distributed, all facilities employ standard operational procedures, share the same layout configuration and use equivalent equipment. They process recyclable materials from municipal selective collection, handling four primary categories: cellulosic materials (paper and cardboard), plastics, metals and glass. The sorting process in all facilities relies on manual separation supported by mechanical systems, such as conveyor belts and baling presses.

Upon arrival via municipal collection trucks, materials undergo an initial pre-sorting stage where workers manually separate cardboard. This cardboard fraction is then directed to

Geographical distribution of studied MRF in Brazil

Highlighting the studied MRF, state capitals and the federal capital.

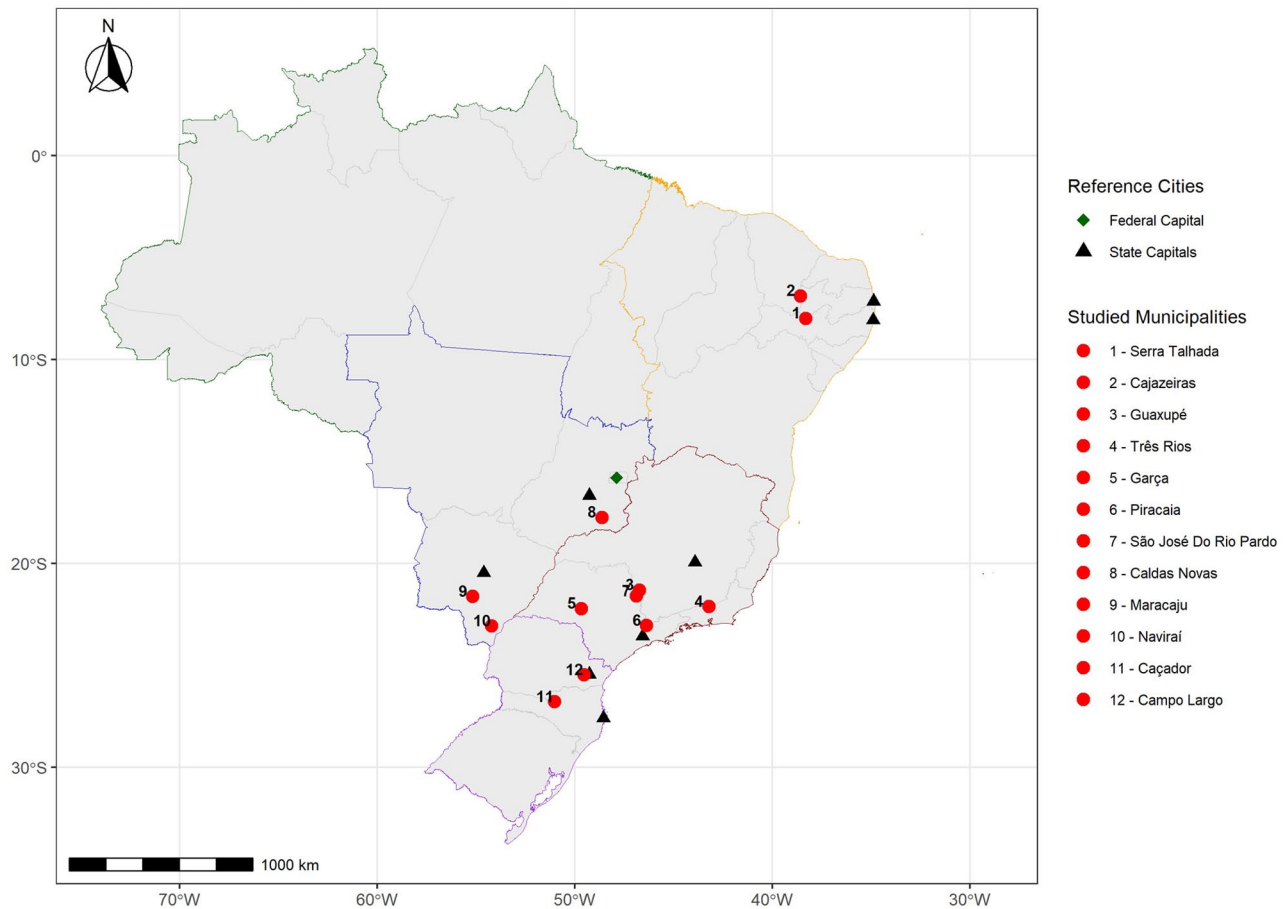


Figure 1. Geographical distribution of studied municipalities in Brazil.

intermediate storage, where it is baled, weighed and transferred to final storage. The remaining materials are conveyed to a sorting belt, where workers perform a detailed manual separation by material type. The sorted fractions are subsequently weighed, stored in big bags or baled (where applicable) before being sent to final storage for sale.

All facilities also process cooking oil and bulky items through dedicated handling streams. Complete descriptions of material inputs, standardised equipment and facility layouts are provided in the Supplemental Material, including process flow diagrams and technical specifications.

Analytical framework

The analytical framework of this study is organised into three categories: operational performance, financial performance and social conditions and decent work. A detailed overview of all metrics, including their definitions and calculation methods, is provided in Table 1. These metrics are used to evaluate the efficiency, financial viability and workforce conditions of the facilities.

Operational performance was assessed using productivity measures, including unit productivity per day, productivity per

worker per day, reject rate, material recovery rate and work efficiency. These measures provide insight into the processing capacity of facilities, the performance of individual workers and the effectiveness of their material sorting processes.

Financial performance was analysed through metrics such as self-sustainability, revenue per mass processed, revenue per mass sold, cost per mass processed and labour cost ratio. These metrics assessed the financial sustainability of the facilities, focussing on their revenue generation, cost efficiency and the proportion of operational costs allocated to labour.

Social conditions and decent work were assessed using metrics such as the number of workers, turnover rate and the extent to which labour costs are covered. These measures provided insights into workforce stability and the sufficiency of revenue to compensate employees, offering a window into worker retention and fair pay.

Statistical analysis

Statistical tests were conducted using the R software version 4.3.1 (R Core Team, 2024), with a significance level of 5%. The Shapiro-Wilk test was used to assess the normality of the data. If

Table 1. Analytical framework: description of the metrics for the operational, financial and social analysis.

Operational performance			
Unit productivity per day (kg day ⁻¹)	Total mass processed daily, indicating the facility's processing capacity	[1]	$\frac{\text{Total mass processed}}{\text{Operating days}}$
Productivity per worker per day (kg worker ⁻¹ day ⁻¹)	Mass sorted per worker each day, measuring individual efficiency	[2]	$\frac{\text{Total mass sorted}}{\text{No. workers} \times \text{Operating days}}$
Reject rate (%)	Percentage of materials discarded after sorting, reflecting process effectiveness	[3]	$\frac{\text{Total reject}}{\text{Total mass sorted}}$
Material recovery rate (%)	Proportion of recyclables successfully recovered and available for sale	[4]	$\frac{\text{Total available for Sale}}{\text{Total mass sorted}}$
Work efficiency (kg h ⁻¹)	Mass sorted per worker per hour, assessing operational efficiency	[5]	$\frac{\text{Productivity per worker per day}}{\text{Hours worked per day}}$
Financial performance			
Financial self-sustainability	Measures the ability of the facility to generate enough revenue from recyclables to cover its costs	[6]	$\frac{\text{Revenue from sales}}{\text{Total operational costs}}$
Revenue per mass processed (USD tonne ⁻¹)	Indicates the average income generated for each metric tonne of material processed	[7]	$\frac{\text{Revenue from Sales}}{\text{Total mass processed}}$
Revenue per mass sold (USD tonne ⁻¹)	Indicates the average revenue for each metric tonne of material sold	[8]	$\frac{\text{Revenue from Sales}}{\text{Total mass sold}}$
Cost per mass processed (USD tonne ⁻¹)	Indicates the cost for processing each metric tonne of material	[9]	$\frac{\text{Total operational costs}}{\text{Total mass processed}}$
Labour cost per mass processed (USD tonne ⁻¹)	Measures the Labour cost required to process one metric tonne of material	[10]	$\frac{\text{Labor cost}}{\text{Total mass processed}}$
Social conditions and decent work			
Number of workers	Average number of workers in the year	[11]	—
Turnover rate (%)	Measures the rate at which workers enter and exit the facility, reflecting workforce stability	[12]	$\frac{\text{No. of entrances} + \text{No. of exits}}{\text{No. of workers}}$
Labour cost coverage ratio	Shows the proportion of revenue from the sale of materials that is 'committed' to ensuring fair wages for workers	[13]	$\frac{\text{Total labor cost}}{\text{Revenue from sales}}$

at least one data series among the analysed cooperatives was found to deviate from a normal distribution, the Kruskal-Wallis hypothesis test was used to verify significant differences, followed by a post hoc Nemenyi test.

Furthermore, a Spearman correlation matrix was generated using MATLAB R2022b (The MathWorks Inc., 2022), which included 11 of the 13 metrics originally proposed in Table 1. Material recovery rate and work efficiency metrics were excluded to avoid redundancy and potential multicollinearity. The Spearman correlation method was chosen over Pearson's correlation due to the non-normal data distribution indicated by the Shapiro-Wilk test, which violates the normality assumption required for Pearson's correlation.

Results and discussion

Gravimetric composition

Figure 2 illustrates the gravimetric composition of the waste sorted in each unit, highlighting materials such as plastics, cellulosic materials, metals and glass. Cellulosic materials were the predominant category, ranging from 43.99% in Campo Largo to 74.85% in Cajazeiras. This dominance can be attributed to its high volume in urban waste streams and the relatively straightforward sorting and processing methods used during the operational process (see Supplemental Figure SM1).

Metals made up the smallest share, ranging from just 2.06% in Maracaju to 9.94% in Campo Largo. Their low recovery is

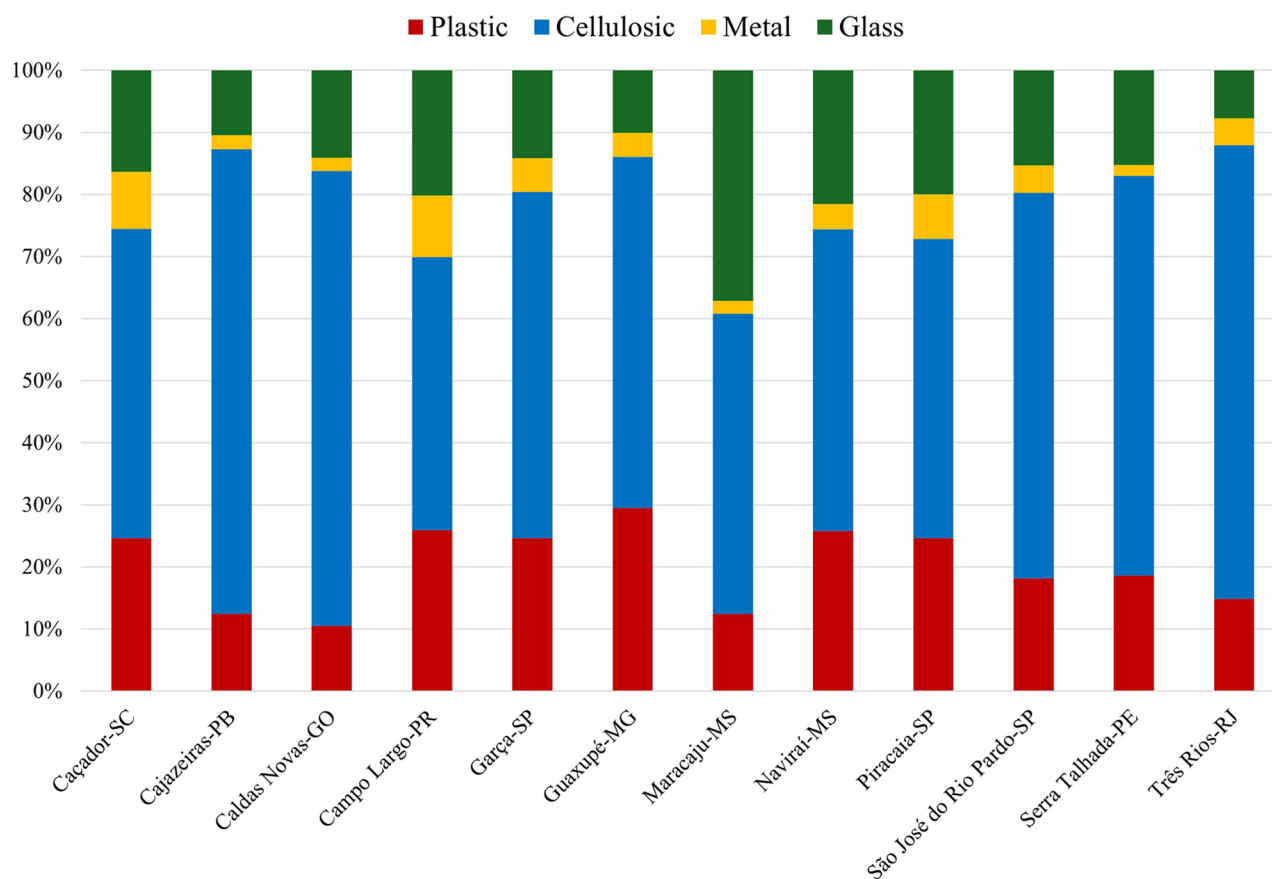


Figure 2. Gravimetric composition of waste sorted.

likely due to informal waste pickers and residents, who often collect high-value metals directly for sale, diverting them from formal recycling channels. Glass generally accounted for a small portion of sorted waste, except in Maracaju (37.14%), where its share was much higher. This is consistent with typical trends, since glass is heavy, has low market value and faces limited demand, factors that often reduce its collection and processing.

Spearman correlation coefficient analysis

The Spearman correlation matrix in Figure 3 and the calculated metrics in Table 2 provide the foundation for the subsequent analyses.

Operational performance

Productivity metrics ([1] and [2]) showed significant differences in the Kruskal-Wallis test, with the most notable differences observed in MRFs located in the cities of Caçador, Campo Largo, Três Rios and Caldas Novas. These MRFs represent those with the two highest and two lowest mean values of material input, respectively. It is important to highlight that the characteristics, particularly quantitative, of materials arriving at an MRF depend

on the availability of selective collection services and the effectiveness of campaigns to engage the population, which are influenced by their sense of community and motivators (Barbosa and Mol, 2018; Yang et al., 2022).

From an internal management perspective, it is important to note that productivity metrics showed a strong negative correlation with processing cost metrics ([9] and [10]), suggesting that higher productivity is associated with lower unit costs. Additionally, there was no correlation between the number of workers and productivity, indicating that simply increasing the size of the workforce does not inherently improve efficiency. This highlights the importance of optimizing workflow organization, training and technological support, rather than relying solely on workforce expansion.

From an external management perspective, it is important to note that productivity does not exhibit a strong correlation with revenue generation. This suggests that improvements in operational efficiency alone do not guarantee higher sales of recyclable materials. This finding underscores the dominant role that external market conditions, rather than internal productivity, play in driving revenue.

With slight variations in the number of workers among the facilities, the workforce ranged from 19 in Garça to 26 in Naviraí. However, due to the variability in material input values, the

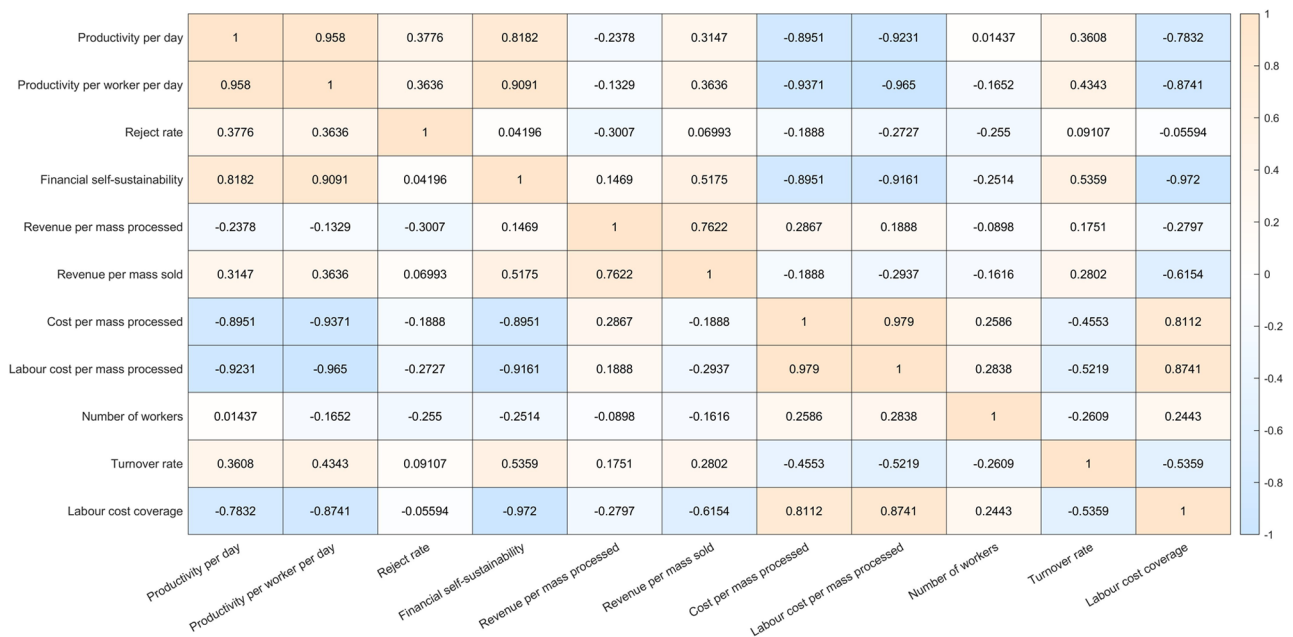


Figure 3. Correlation matrix derived from the Spearman correlation coefficient analysis.

worker productivity showed a significant difference in the Kruskal-Wallis test. The Nemenyi test revealed the most differences in the cities of Caçador, Cajazeiras, Piracaia and Três Rios. These cities again represent those with the highest and lowest median and average worker productivity values, as shown in Figure 4(a) and Table 2. The use of non-parametric tests is justified by the identification of at least one non-normal distribution in the Shapiro-Wilk test.

The material recovery rate ranged from 57.62% in Caçador to 89.93% in Caldas Novas, with corresponding reject rates varying from 42.38% to 10.07%, and an average rate of 17.71%. This range is consistent with studies conducted in other well-structured cooperatives in Brazil, which reported reject rates of 17% in Ribeirão Pires (King and Gutberlet, 2013) and 10.9% in Cachoeira de Minas (Sakamoto et al., 2021). However, higher rejection rates have also been observed, such as 30.5% in Blumenau (Moura et al., 2018) and over 40% in São José dos Campos (Ferro and de Souza, 2024). A significant difference in rejection rates was found using the Kruskal-Wallis test, with the Nemenyi test highlighting the largest disparities between Caçador and Campo Largo.

The reject rate exhibits a moderate positive correlation with productivity. However, it does not exhibit strong correlations with other operational or financial variables. This suggests that higher processing speed may slightly increase material rejection, meaning that productivity does not necessarily indicate better sorting quality. These findings highlight the need for performance evaluations that go beyond throughput, emphasizing the influence of external factors on rejection levels. The high inter-quartile range of rejection levels may indicate greater qualitative variability in the materials available in MRFs, potentially due to

inadequate separation of recyclables at the household level or fluctuations in the regional material sales market.

Financial performance

Self-sustainability. Financial self-sufficiency varies considerably across the units analysed, ranging from 23.85% to 78.35%, with an overall average of 46.01%. While only two units reach a value above 70%, most fall below this threshold. The lowest values are observed in Serra Talhada, Piracaia and São José do Rio Pardo, all below 32%.

These results highlight the difficulties faced by most facilities in covering their operational costs through recyclables revenue alone, underlining their financial vulnerability. It is important to note that the analysed units benefit from full technical support provided by the Instituto Recicleiros, which offers expertise and detailed monitoring in organizational, structural, operational and financial aspects (including tax and formal registration). However, in contrast, most MRFs in Brazil are managed by cooperatives, which assume full responsibility for all aspects of operation but lack adequate support and training from both public and private initiatives. Additionally, these MRFs often lack the necessary infrastructure and equipment, further limiting their ability to achieve financial sustainability.

Revenue generation. Comparing revenue generation metrics based on mass processed versus mass sold reveals differences in financial performance. While both metrics quantify revenue generation, their divergence highlights operational challenges, such as processing losses, variations in material quality, market fluctuations and stock management practices.

Table 2. Metrics for assessing operational, economic, social and working conditions in facilities.

Facility	Operational performance			Financial performance			Social conditions and decent work						
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Caçador	3830.25	191.51	42.38%	57.62%	23.94	71.95%	8.01	12.14	11.13	8.09	20	81%	101.03%
Cajazeiras	2032.3	86.64	15.39%	84.61%	10.83	33.70%	7.72	9.05	22.90	17.66	23	17%	228.80%
Caldas Novas	1483.09	74.15	10.07%	89.93%	9.27	40.08%	7.76	9.03	19.36	16.39	20	63%	211.22%
Campo Largo	3565.69	178.28	26.90%	73.10%	22.29	70.40%	9.91	14.31	14.07	9.50	20	33%	95.90%
Garça	1910.19	100.54	17.52%	82.48%	12.57	52.82%	10.53	10.75	19.93	14.14	19	37%	134.29%
Guaxupé	2938.76	117.94	14.06%	85.94%	14.74	54.27%	7.63	9.26	14.05	11.73	21	18%	153.80%
Maracaju	2790.75	121.34	11.96%	88.04%	15.17	78.35%	14.55	17.44	18.57	12.96	23	53%	89.06%
Naviraí	2114.41	81.05	14.52%	85.48%	10.13	39.09%	9.97	11.07	25.51	16.64	26	51%	166.81%
Piracaia	1078.63	50.64	15.18%	84.82%	6.33	24.17%	9.93	10.59	41.08	27.18	21	22%	273.72%
São José do Rio Pardo	1158.39	57.84	14.74%	85.26%	7.23	31.32%	11.09	13.41	35.42	25.83	20	23%	232.78%
Serra Talhada	1755.39	73.64	19.64%	80.36%	9.2	23.85%	6.49	7.52	27.22	20.05	23	30%	308.86%
Três Rios	1314.98	59.77	10.12%	89.88%	7.47	32.13%	11.02	12.13	34.31	24.51	22	18%	222.31%
Mean	2164.40	99.44	17.71%	82.29%	12.43	46.01%	9.55	11.39	23.63	17.05	-	37.17%	184.88%

Operational performance: [1] – productivity per day (kg day⁻¹); [2] – productivity per worker per day (kg worker⁻¹ day⁻¹); [3] – reject rate; [4] – material recovery rate; [5] – work efficiency (kg h⁻¹) | financial performance: [6] financial self-sustainability; [7] revenue per mass processed (USD tonne⁻¹); [8] revenue per mass sold (USD tonne⁻¹); [9] cost per mass processed (USD tonne⁻¹); [10] labour cost per mass processed (USD tonne⁻¹) | social conditions and decent work: [11] number of workers; [12] turnover rate; [13] labour cost coverage. See Table 1 for the description and calculation method of each metric.

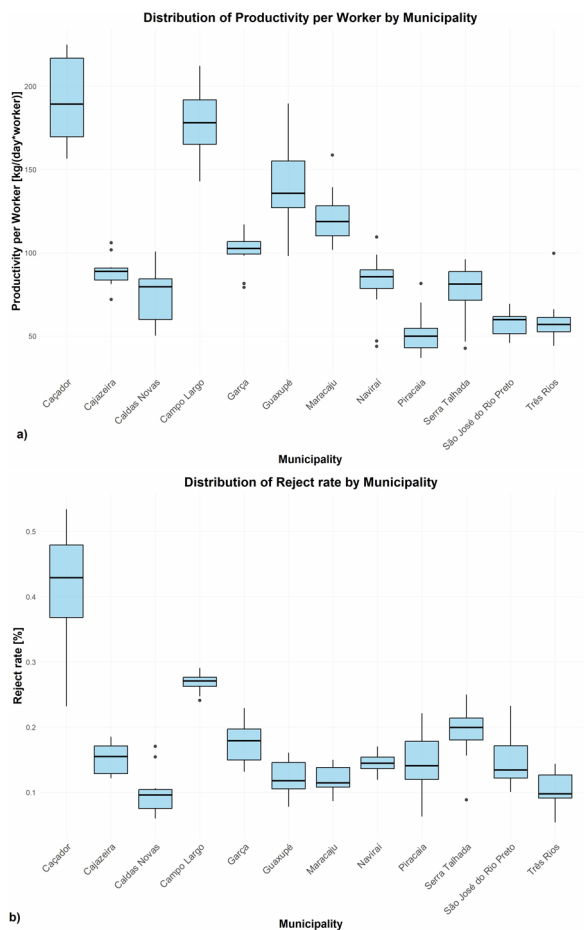


Figure 4. Operational metrics boxplots distributions (a) productivity per worker by municipality studied (b) reject rate.

On average, the revenue per mass processed (9.55 USD tonne^{-1}) is typically lower than the revenue per mass sold (11.39 USD tonne^{-1}). This is because both metrics use the same sales revenue, but the total mass processed exceeds the total mass sold. Not all incoming material is immediately marketable – some is lost during processing, stockpiled or discarded. Furthermore, revenue differences arise from the need to accumulate certain recyclables before sale, as some fractions require larger volumes to be commercially viable. Consequently, sales revenue may include materials processed in previous years but only sold once sufficient stock was available. This temporal mismatch between processing and sales further contributes to the variation between the two metrics. In particular, facilities such as Garça and Piracema exhibit a smaller gap between their revenue metrics, suggesting a relatively balanced material intake and sales.

Higher revenue per mass sold, such as in Campo Largo and Maracaju, may suggest favourable market conditions or a focus on high-value materials. However, this does not necessarily indicate better operational performance. Conversely, lower values in places like Serra Talhada could signal weaker market demand or stockpiling of unsold materials. In these cases, the revenue gap underscores the need for strategies to mitigate market

fluctuations, improve access to stable buyers, and optimize inventory management.

The correlation between revenue-related metrics and self-sustainability is moderate, suggesting that while higher revenues contribute to long-term viability, they are not the sole factor. Other structural and operational elements likely play an important role in maintaining financial health.

Costs. The cost per mass processed exhibits significant variation, ranging from 11.13 USD tonne^{-1} to 41.08 USD tonne^{-1} , with an average of 23.63 USD tonne^{-1} . This variability can be attributed to several factors, including facility processing capacity, waste composition and regional economic conditions.

Figure 3 reveals a trend observed in the data set, that facilities processing higher volumes of waste tend to achieve lower processing costs per tonne. This finding aligns with the work of Cimpan et al. (2016), who highlighted the importance of economies of scale in cost efficiency. Their study demonstrated that increasing facility capacity from 25,000 to 100,000 tonnes per year could reduce costs, driven by improved resource allocation and operational efficiency. Although the facilities analysed in our study operate at significantly lower capacities, the same principle applies: Larger scale operations benefit from cost reductions due to higher throughput and more efficient utilization of labour and machinery.

However, when the studied facilities are compared with large-scale commercial MRFs, an interesting contrast emerges. For example, Olafasakin et al. (2023) reported an operating cost of 45.48 USD tonne^{-1} for a 120,000 tonnes per year MRF, which is notably higher than the average cost observed our study. This suggests that while economies of scale generally lead to cost reductions, other factors, such as labour intensity, automation levels and local economic conditions, also play a critical role in determining operational costs.

The configuration of these facilities is another significant factor that influences cost variability. According to Pressley et al. (2015), operational costs (excluding capital expenses) vary significantly depending on the system design. Mixed-waste facilities had the lowest costs at 3.7 USD tonne^{-1} , while single-stream processing exhibited the highest at 6.9 USD tonne^{-1} . Intermediate values were observed for dual-stream and pre-sorted systems, with costs of 5.7 and 4.2 USD tonne^{-1} , respectively. The facilities analysed in our study use a single-stream processing system, which is consistent with the operational costs reported for this configuration.

However, the average cost observed (23.63 USD tonne^{-1}) is substantially higher than the range reported by Pressley et al. (2015). This discrepancy can probably be attributed to differences in scale, regional economic conditions and labour costs, as well as potential inefficiencies in smaller scale MRFs operating in Brazil. Additional contributing factors may include lower levels of automation, greater reliance on manual sorting and logistical constraints. These elements collectively explain the elevated

costs observed in the present study, underscoring the complex interplay of operational and regional factors in determining MRFs economics.

The labour cost per metric tonne of processed material ranges from 8.09 to 27.18 USD tonne⁻¹, with an average of 17.05 USD tonne⁻¹. This average labour cost is notably higher than the labour costs reported in studies of facilities in other countries, such as those of Pressley et al (2015).

A nearly perfect correlation between the cost per mass processed and labour cost per mass processed confirms that labour expenses are a major component of total processing costs. From a socio-economic perspective, while higher labour costs may reflect fairer worker compensation, which is a critical factor in Brazil, they also highlight the financial unsustainability of many MRFs. Without revenue streams (e.g. tipping fees, government subsidies or private partnerships) to offset these costs, facilities face persistent financial vulnerability.

Social and decent work. The turnover rate values ranged from 81% to 17%, with an average of 37% across the units. Hancock et al. (2013) highlighted a strong negative relationship between turnover rates and organizational performance, with this behaviour being most pronounced in the manufacturing sector, a sector in which the MRFs studied can be included, according to the Brazilian definition of economic activities, due to their material processing operations such as plastic baling and glass crushing (IBGE, 2023). Furthermore, turnover rates in an organization can negatively impact other critical aspects, such as financial revenue and occupational safety, as noted by Shaw (2011).

The turnover rate shows a moderate negative correlation with labour cost coverage, indicating that higher turnover of the workforce reduces a facility's ability to cover labour expenses. Among the MRFs analysed, only two generated enough revenue from recyclable sales to at least cover fair wages for workers (here considered as the current minimum wage under Brazilian legislation). It is important to note that all facilities in this study receive financial support from the Instituto Recicleiros, which ensures that workers earn at least the minimum wage regardless of sales revenue.

An analysis of the labour cost coverage metric reveals that labour costs exceed the total available revenue from material sales by significant percentages. It should be noted that this metric only considers wage costs, without including other operational expenses, demonstrating the severe financial deficit faced by the MRFs studied under Brazil's current waste management framework.

Previous studies have documented cases of low wages in the recycling sector. In South Africa, Bala et al. (2023) highlight the low earnings of workers involved in plastic resin recycling and emphasize the need for government intervention to support the industry, such as extended producer responsibility (EPR)

policies, to increase profitability and, consequently, improve worker compensation. In Pakistan, Shaikh et al. (2020) align with the findings of this study by showing that recycling costs exceed worker earnings by 2.6–4.7 times. They also argue for joint efforts between government and industry to improve the profitability of the recycling sector and maximize its social and environmental benefits.

Revenue models and financial sustainability of MRFs

The correlation analysis reveals that while higher productivity is related to lower unit processing costs, it does not directly translate into increased revenue. This highlights the significant role of external market conditions in revenue generation, making MRFs vulnerable to price fluctuations in the recycling market. Moreover, financial sustainability depends on the stability of worker compensation, which affects turnover rates, labour costs and operational efficiency.

Building on the data-driven analysis conducted in previous sections and the interconnections between operational, financial and labour aspects, we propose the revenue models framework presented in Figure 5. The first model (Figure 5(a)), which combines revenue from both material sales and service payments, offers a more predictable income stream. This stability allows for consistent worker compensation, reducing turnover and fostering greater formalization within the sector. A stable workforce reduces recruitment and training costs, improving productivity and decreasing operational expenses. In contrast, the second model (Figure 5(b)), which is based solely on material sales, exposes MRFs to income volatility. This system, which predominates in Brazil, leads to inconsistent wages, high turnover and increased informality, driving up labour costs and diminishing productivity, thus perpetuating a cycle of financial instability.

To address the financial challenges of a market-dependent model, researchers have identified different remuneration mechanisms. These aim to diversify income sources by recognizing waste management as an essential environmental service, not just a commercial activity. For instance, an initiative in Minas Gerais, Brazil, compensates waste picker cooperatives based on the type and volume of recyclables processed. This approach acknowledges the environmental benefits of recycling, such as reduced emissions and resource conservation, rather than covering collection and sorting services (Dias, 2016; Dias et al., 2022; Santana et al., 2022).

Another model found in the literature involves private sector partnerships, where waste picker cooperatives collaborate with businesses to manage non-household waste, including materials from industries, offices and events. The literature also explores a third approach that centres on EPR, or logistic reverse systems as they are known in Brazil (Gutberlet and Carengo, 2020; Rutkowski and Rutkowski, 2015).

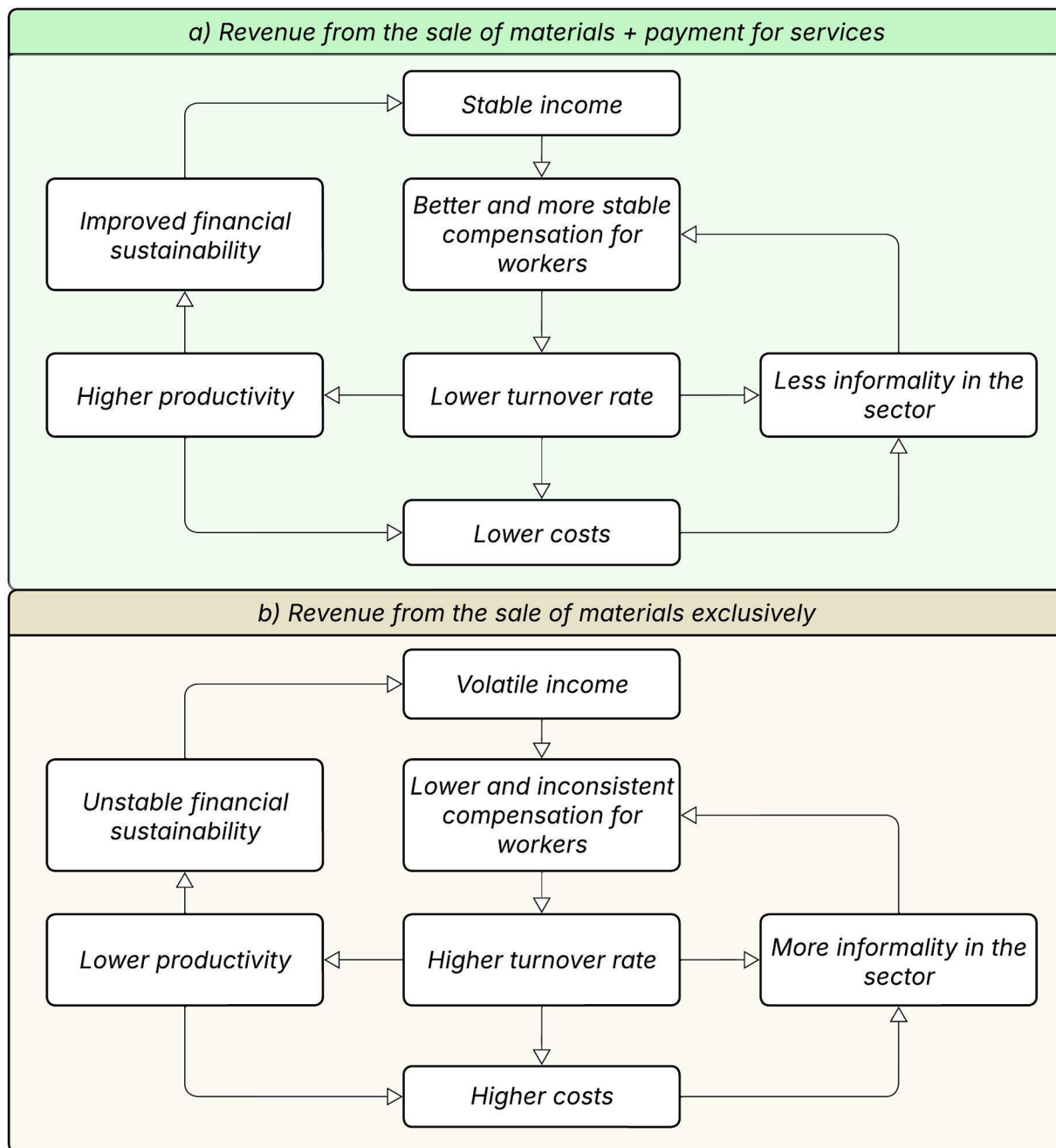


Figure 5. Revenue models framework for MRFs (a) from both material sales and service payments (b) based solely on material sales.
MRF: material recovery facility.

Conclusions

This study revealed a complex interplay of operational, economic and social factors constraining the financial viability of MRFs. While higher productivity correlates with lower unit costs, it does not inherently translate to better sorting quality or increased revenue, as reject rates remain weakly influenced by throughput. Instead, revenue generation is largely dictated by volatile recyclables markets, emphasizing the need for policies that stabilize prices and improve access to reliable buyers.

A critical finding is the disconnect between labour costs and income – wage expenses averaged 1.84 times revenue from recyclable sales, making fair compensation unsustainable without external subsidies, such as those provided by Instituto Recicleiros. High turnover further strains operations, perpetuating financial instability. This underscores the limitations of Brazil’s prevailing revenue model (Figure 5(b)), which is based solely on material sales and does not reconcile labour needs with market realities.

The formalization of informal waste pickers into cooperatives, though essential, demands more than structural inclusion.

Initiatives such as the ‘Waste Pickers Academy’ (Recicleiros, 2024) and UNICATA (Gutberlet and Vallin, 2024) demonstrate the importance of targeted training and institutional support to enable this transition.

However, these efforts alone are insufficient, as systemic reforms remain essential for sector-wide improvement, particularly in countries of the Global South. Implementing EPR policies and market stabilisation measures would establish more favourable conditions for MRFs to operate sustainably. Without such comprehensive reforms, even the most efficient cooperatives will continue to face structural challenges within Brazil’s current waste management framework.

Finally, we acknowledge as a limitation that the framework presented in Figure 5 is qualitative and supported only by empirical correlations. Parametrized modelling or scenario simulations to quantify how alternative revenue structures would affect revenues, wages, turnover and unit processing costs are beyond the scope of this study and should be addressed in future work.

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Not applicable.

Consent for publication

Not applicable.

Consent to participate

Not applicable.

Data availability statement

The data that support the findings of this study are available from Instituto Recicleiros but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Instituto Recicleiros. All data generated during using the data set are included in this published article [and its Supplemental Material].

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Supplemental material

Supplemental material for this article is available online.

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