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Proposal for a new evaluation protocol for recyclable waste recovery units: an overview of the western region of the state of Paraná - Brazil

Proposta de um novo protocolo de avaliação de unidades de valorização de resíduos recicláveis: um panorama da região oeste do estado do Paraná, Brasil

Anderson Junior Turmina[1], *Juliana Elisabete Correia*[2], *Katia Valeria Marques Cardoso Prates*[3], *Fabiana Bassani*[4,5], *Larissa Maria Silveira Pereira*[1], *Thiago Edwiges*[1]

ABSTRACT

Brazil generates more than 81 million tons of municipal solid waste (MSW) annually, of which only approximately 30% is potentially recyclable. Despite this, only 3% of this overall amount is recovered, mainly due to the lack of adequate structures for sorting and recovering waste. This low utilization compromises the efficiency of selective collection, increases environmental impacts, and limits the socioeconomic inclusion of waste pickers. Given this scenario, this study aimed to develop a new evaluation protocol for Material Recovery Facility (MRF), based on qualitative and quantitative indicators to identify the quality of the MRFs. The protocol development steps included defining the objective; defining the criteria and indicators; defining the evaluation method; defining the sampling unit for protocol application; collecting data; and analyzing the results. The methodology involves the definition of 12 indicators: location, infrastructure, safety, environmental health, sustainable resources, waste pickers' association/cooperative, regularization and licensing, protection, support infrastructure, materials and equipment, operational monitoring, accounting/income/benefits distributed in four categories: physical, environmental, technical-operational, and socioeconomic. The evaluation protocol was applied to 34 MRFs in the western region of Paraná in 2024, participants in the Waste Management Program of Itaipu Binacional. Out of the 34 MRFs, 44% were classified as *excellent*, and 56% were classified as *good*, meeting 76–96 and 56–74% of the indicators, respectively. Average efficiencies

RESUMO

O Brasil gera mais de 81 milhões de toneladas de resíduos sólidos urbanos (RSU) por ano, das quais cerca de 30% são potencialmente recicláveis. Apesar disso, apenas 3% desse total é efetivamente recuperado, em razão principalmente da falta de estrutura adequada para triagem e valorização dos resíduos. Esse baixo aproveitamento compromete a eficiência da coleta seletiva, acentua os impactos ambientais e limita a inclusão socioeconômica de catadores. Diante desse cenário, o presente estudo teve como objetivo desenvolver um novo protocolo de avaliação para Unidades de Valorização de Resíduos Recicláveis (UVR), baseado em indicadores qualiquantitativos para identificar a qualidade das UVR. As etapas de elaboração do protocolo incluíram: definição do objetivo; definição dos critérios e indicadores; definição do método de avaliação; definição da unidade amostral para aplicação do protocolo; coleta de dados; e análise dos resultados. A metodologia adotada envolveu a definição de 12 indicadores, quais sejam: localização, infraestrutura, segurança, salubridade do ambiente, recursos sustentáveis, associação/cooperativa de catadores, regularização e licenciamentos, proteção, infraestrutura de apoio, materiais e equipamentos, monitoramento operacional, contábil/renda/benefícios, distribuídos em quatro categorias: físico, ambiental, técnico-operacional e socioeconômico. O protocolo de avaliação foi aplicado em 34 UVR da região oeste do Paraná em 2024, que eram participantes do Programa de Gestão de Resíduos da Itaipu Binacional. Das 34 UVR avaliadas, 44% foram classificadas com qualidade excelente e 56% foram classificadas com

[1]Federal Technological University of Paraná – Medianeira (PR), Brazil.

[2]Itaipu Parquetc – Foz do Iguaçu (PR), Brazil.

[3]Federal Technological University of Paraná – Londrina (PR), Brazil.

[4]Federal Institute of Pará – Conceição do Araguaia (PA), Brazil.

[5]University of Coimbra, Department of Mechanical Engineering – Coimbra, Portugal.

Corresponding author: Thiago Edwiges – Avenida Brasil, 4232 – Independência – CEP: 85884-000 – Medianeira (PR), Brazil. E-mail: thiagoe@utfpr.edu.br

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of 85, 77, 59, and 57% were observed for the technical-operational, physical, environmental, and socioeconomic categories, revealing that, even with adequate infrastructure, MRFs still require improvements related to health, sustainability, and the social development of their members. However, all MRFs presented high-quality indices (above 28 points), suggesting that the management of these units, especially those classified as *excellent,* is aligned with the best practices in the industry and has been efficient in managing recyclable waste. The results confirm that this new protocol is an effective tool for diagnosing, monitoring, and directing continuous improvement actions in MRFs, in addition to offering support in formulating public policies.

Keywords: performance indicators; qualitative and quantitative assessment; municipal solid waste management; recycling cooperatives; quality index.

qualidade boa, atendendo entre 76–96 e 56–74% dos indicadores, respectivamente. Foram observadas eficiências médias de 85, 77, 59 e 57% para as categorias técnico-operacional, físico, ambiental e socioeconômico, revelando que, mesmo com infraestrutura adequada, as UVR ainda requerem melhorias relacionadas à salubridade, sustentabilidade e desenvolvimento social dos cooperados. Contudo, todas as UVR apresentaram índices de qualidade elevados (acima de 28 pontos), sugerindo que a gestão destas unidades, especialmente aquelas classificadas com qualidade excelente, está alinhada às melhores práticas do setor e tem sido eficiente no gerenciamento dos resíduos recicláveis. A análise de sensibilidade revelou que 13 parâmetros apresentaram maior relevância, indicando um foco de intervenções prioritárias nas UVR avaliadas. Os resultados confirmam que este novo protocolo é uma ferramenta eficaz para diagnóstico, monitoramento e direcionamento de ações de melhoria contínua nas UVR, além de oferecer suporte à formulação de políticas públicas.

Palavras-chave: indicadores de desempenho; avaliação qualiquantitativa; gestão de resíduos sólidos municipais; cooperativas de reciclagem; índice de qualidade.

Introduction

In today's society, the management of municipal solid waste (MSW) has become a major global challenge. Common MSW components include paper, metals, glass, plastics, food waste, and street-cleaning waste, all of which exhibit highly heterogeneous compositions. Rapid urban population growth increases the demand for goods and services, leading to higher consumption and waste generation. As a result, urban environmental pressure rises, affecting both quality of life and ecological stability (Kaza et al., 2018; Ferronato and Torreta, 2019; UNEP, 2024; Voukkali et al., 2024).

Brazil has a population of approximately 211.1 million inhabitants (IBGE) and generates, on average, 1 kg of MSW per capita per day (Brasil, 2022). Of this total, 39.2% consists of recyclable materials, representing an estimated 30.2 million tons of recyclables generated annually nationwide (Brasil, 2022). These numbers underscore the substantial potential for recyclable recovery and the need for effective strategies to utilize them. MSW recycling can contribute directly to sustainability targets by promoting resource recovery, reducing energy use, and lowering atmospheric emissions (Pressley et al., 2015).

However, the recyclability of MSW depends strongly on market dynamics. Even when recycling potential is high, system effectiveness is conditioned by the proximity to urban centers to industrial facilities and by regulatory and financial public policies (Toso and Alem, 2014; Besen et al., 2023; Bruhn et al., 2023). The European Union established recycling and reuse targets of at least 55, 60, and 65% by weight for 2025, 2030, and 2035, respectively, under Directive 2008/98/EC (Le Pera et al., 2023). Recycling rates in countries such as the United States and South Korea reached 32 and 57%, respectively (Chertow et al., 2024). In contrast, Brazil shows considerably lower recovery rates for dry recyclables, ranging from 0.19 to 5.44%, with national goals of 9.2% by 2028 and 20% by 2040 (Brasil, 2022).

According to ABREMA (2024), MSW generation in Brazil has increased slightly in 2023, by less than 1%, reaching 1.05 kg per capita per day, or more than 221,000 tons of MSW per day nationwide. The 2023 ABREMA report (ABREMA, 2023) also indicates that MSW generation in 2022 decreased by approximately 2% compared with 2021, from around 226,000 tons per day (1.07 kg per capita) to 221,000 tons per day (1.04 kg per capita).

These variations are closely linked to the socioeconomic changes triggered by the Covid-19 pandemic. Social isolation reduced waste generation from commercial establishments but significantly increased household waste. The rapid expansion of e-commerce and delivery services intensified the disposal of packaging materials such as cardboard and plastics, altering the gravimetric composition of household waste. Despite the rise in recyclable materials, recycling cooperatives faced operational constraints due to temporary lockdowns and reduction in selective collection services in several municipalities (Silva et al., 2022).

Insufficient infrastructure for waste collection, transportation, and disposal contributes to the improper disposal of MSW in vacant lots, waterways, and other unsuitable sites. This scenario leads to soil, water, and air pollution and favors the proliferation of disease vectors, the emission of greenhouse gases, and the degradation of urban landscapes (Maiello et al., 2018; Abubakar et al., 2022). Addressing these issues requires integrated MSW management actions, including waste reduction, treatment, reuse, recycling, and environmentally sound final disposal. These actions also support income generation and employment, partic-

ularly for waste pickers. In this context, recycling cooperatives and associations play a crucial role in selective collection and the valorization of recyclable materials, contributing to environmental sustainability and impact reduction (Paoli and Melo, 2015; São Bento and Carneiro, 2024).

Despite their relevance, cooperatives and associations recover only about 3% of recyclable materials in Brazil (Guabiroba et al., 2023). Major barriers to implementing effective selective collection include limited or absent financial support from public incentive policies and low levels of environmental awareness among the population (Yukalang et al., 2017; Gutberlet, 2021). Consequently, there is a clear need for evaluation tools that reflect on the operational conditions of recycling centers and help identify and address bottlenecks in recyclable waste management. Studies also show that the selection of indicators and the aggregation of results strongly influence the comparability and practical applicability of quality protocols (Pressley et al., 2015; Cetrulo et al., 2020; Le Pera et al., 2023; Liu et al., 2024; Chertow et al., 2024; Bradshaw et al., 2025).

Although several consolidated quality indices exist, such as the Waste Landfill Quality Index (IQR), the Composting Plant Quality Index (IQC), and the Transfer Station Quality Index (IQT) (CETESB, 2023),these tools were designed for other types of facilities and do not cover the specific infrastructural requirements of recyclable waste management units. Recent studies have advanced the evaluation of selective collection systems and cooperative networks (Macagnan and Seibert, 2021; Guabiroba et al., 2023; Pisano et al., 2024). However, most remain limited to narrow sets of indicators or focus predominantly on environmental aspects, without integrating technical, operational, and socioeconomic dimensions. By incorporating both national and international references, this study proposes an integrated model that combines physical, environmental, technical-operational, and socioeconomic indicators within a single evaluation framework.

The application of such a framework can support public managers and material recovery facilities (MRF) in prioritizing investments and designing more effective public policies for the strengthening and expansion of MRF in other regions. In countries such as the United States where HDI and GDP per capita indicators are higher, approximately 91% of the population has access to recycling programs associated with broader waste recovery structures (Bradshaw et al., 2025). In this context, the present study proposes a comprehensive qualitative-quantitative protocol better suited to the Brazilian context, with a specific focus on the operational characteristics of MRFs. This approach addresses a methodological gap and provides guidance for both local management and the formulation of public policy.

Material and Methods

Development of an evaluation protocol for Material Recovery Facilities

The protocol used to evaluate the performance of MRFs was designed to support both the monitoring of individual facilities and comparisons among facilities within a waste planning and management unit. The methodology combines qualitative and quantitative approaches through the definition of indicators and the assignment of weights, utilizing Microsoft Excel for data analysis and interpretation (Figure 1). The development of the protocol involved the following steps: defining the objective; establishing criteria and indicators; selecting the evaluation method; determining the sampling unit for protocol application; collecting data; and analyzing the results.

Definition of the objective of the protocol, criteria, and indicators

In Stage 1, the goals for evaluating and monitoring the performance of different MRFs were defined. To support this step, managers and technical staff from the Itaipu Binacional solid waste management program were consulted, along with professionals directly responsible for MRF operations.

In Stage 2, the categories and indicators for constructing the Quality Index Protocol for MRFs (MRF-QI) were established (Figure 2). The methodology was based on nationally recognized models, including the Waste Landfill Quality Index (IQR), the Composting Plant Quality Index (IQC), and the Transfer Station Quality Index (IQT), developed by the Environmental Company of the State of São Paulo (CETESB, 2023). These indices are widely acknowledged for their robustness and reliability in solid waste management and are supported by a long-standing historical dataset in the State of São Paulo.

The sustainability indicators and their respective parameters for evaluating quality in the environmental, social, economic, and operational dimensions (Table 1) were selected through document analysis, on-site visits, bibliographic research, and consultation of legal regulations, including Law 10.257/2001 (City Statute), Law No. 12.305/2010 (National Solid Waste Policy), Law No. 12.690/2012 (Organization and Operation of Work Cooperatives), Regulatory Standards such as 06 (PPE), 24 (Sanitary and Comfort Conditions in the Workplace), and 38 (Occupational Safety and Health in Urban Cleaning and Solid Waste Management Activities) of the Ministry of Labor, ABNT NBR 9050/2015 (Accessibility to buildings, furniture, and spaces).

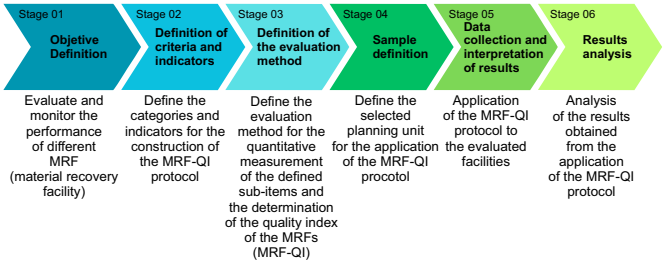

Figure 1 – Stages in the development of the evaluation protocol for the Quality Index of MRF.

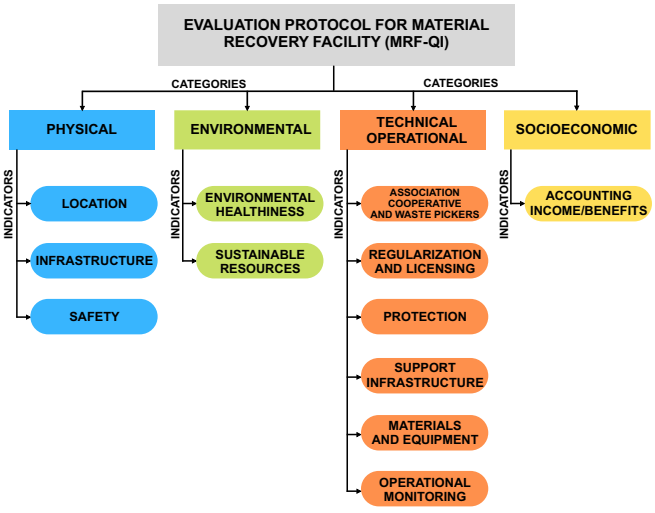

Figure 2 – Flowchart for the MRF-QI.

The relevance of these indicators lies in their ability to reflect compliance with legal standards and the operational efficiency of the facilities, ensuring proper environmental, social, and economic management of waste.

MRF-QI evaluation method

In Step 3, the evaluation method used was defined to quantitatively measure the analyzed parameters and to determine the QI-MRF. The proposed protocol was developed using the Microsoft Excel® software, as illustrated in Figure 3. Identification data for each MRF was entered at the top of the spreadsheet, including municipality, geographic location, facility identification, evaluator, and evaluation date. The categories, indicators, and corresponding parameters were then presented in parallel. For each parameter, a descriptive question was formulated, with binary yes/no response options. This structure was adopted to facilitate the evaluation process and to reduce subjectivity. Scores of 0 or 1 were assigned to each response, indicating non-conformity or conformity, respectively, based on the evaluated parameter.

The MRF-QI corresponds to the cumulative score obtained across the four categories, with a maximum possible total of 50 points. These points were distributed as follows: 10 points for the physical category, 10 points for the environmental category, 25 points for the technical-operational category, and 5 points for the socioeconomic category. For the combined qualitative and quantitative assessment, a classification scheme was established based on the total score achieved. The 50-point scale was divided into four proportional ranges: *excellent* (38–50 points), *good* (26–37 points), *insufficient* (13–25 points), and *poor* (0–12 points). These classes represent the overall quality of the MRF according to its observed performance.

Table 1 – Categories, indicators and parameters of the MRF-QI.

Category	Indicator	Parameter
Physical	Location	Land use and occupation
		Environmental Preservation Area (EPA)
		Adequate access road
	Infrastructure	Adequate physical space
		Accessibility
		Adequate internal yard
		Lighting
		Ventilation
	Safety	Isolation and access control
		Security surveillance
Environmental	Environmental healthiness	Excessive odor
		Disease vectors
		Waste accumulation
		Hazardous waste
		Leachate
	Sustainable resources	Rainwater harvesting and reuse system
		Renewable energy
		Natural lighting
		High-efficiency lighting
		Thermal/acoustic insulation
Technical-operational	Association, cooperatives and waste pickers	Productivity
		Association/cooperative
		Association/cooperative regularization
		Child labours
		Technical guidance
		Training and capacity building
		Inclusion of autonomous waste pickers
	Regularization and licensing	Property ownership
		Business license
		Documentary restrictions
		Environmental licensing
		Fire department approval
	Protection	Insalubrity parameters
		Staff uniform
		Individual protection equipment (IPE's)
		Collective protection equipment (CPE's)
	Support infrastructure	Administrative sector
		Kitchen or canteen
		Sanitary/dressing rooms
	Materials and equipment	Office supplies
		Adequate equipment
		Equipment conservation
	Operational monitoring	Data access
		Residual waste and recycling rate
		Attendance monitoring
Socioeconomic	Accounting, income and benefits	Accounting and invoice control
		Adequate income
		Agreements
		Qualification support
		Life insurance

EVALUATION PROTOCOL FOR MATERIALS RECOVERY FACILITY (MRF)

Municipality:								Year:	**2024**	
Coordinate/Location:			**MRF identification:**		**Evaluator:**					
			Representative:							
Categories		**Indicators**	**No.**	**Parameters**	**Description**	**Yes**	**No**	Fill In Points	**Accumulated**
PHYSICAL	A	LOCATION	1	LAND USE AND OCCUPATION	Is the MRF location in accordance with municipal land use and occupation legislation?	1	0	0	0,00
			2	ENVIRONMENTAL PRESERVATION AREA (EPA)	Is the MRF not located in a permanent preservation area (EPA)?	1	0	0	
	B	INFRASTRUCTURE	3	ADEQUATE ACCESS ROAD	Does the MRF have a paved and signposted access road to the MRF site?	1	0	0	
			4	ADEQUATE PHYSICAL SPACE	Does the MRF have an adequate internal space for waste management, sorting, and storage?	1	0	0	
			5	ACCESSIBILITY	Does the MRF present accessibility for PWD (Person with Disabilities) in the work area? - Ex: Adapted restroom, adequate circulation, etc.	1	0	0	
			6	ADEQUATE INTERNAL SPACE	Does the MRF have an internal area that is suitable for the circulation and parking of vehicles?	1	0	0	
			7	LIGHTING	Is there adequate lighting (visual analysis)?	1	0	0	
			8	VENTILATION	Is there a ventilation system (windows, exhaust, insufflation system)?	1	0	0	
	C	SAFETY	9	ISOLATION AND ACCESS CONTROL	Does the MRF have some type of isolation (fence, wall, or enclosure) and access control (guardhouse)?	1	0	0	
			10	SECURITY SURVEILLANCE	Does the MRF have security systems (cameras, alarms, or vigilance)?	1	0	0	
ENVIRONMENTAL	D	ENVIRONMENTAL HEALTHINESS	11	EXCESSIVE ODOR	Is there excessive odor?	0	1	0	0,00
			12	DISEASE VECTORS	Is there disease vectors such as flies, mosquitoes, insects, birds, and small animals?	0	1	0	
			13	WASTE ACCUMULATION	Is there waste accumulation in the internal or external space of the MRF?	0	1	0	
			14	HAZARDOUS WASTE	Is there presence or storage of hazardous waste harmful to health and/or the environment? - Ex: paint residue, solvents, fuels, acids, etc.?	0	1	0	
			15	LEACHATE	Is there leachate?	0	1	0	
	E	SUSTAINABLE RESOURCES	16	RAINWATER HARVESTING AND REUSE SYSTEM	Does the MRF have rainwater harvesting and reuse systems?	1	0	0	
			17	RENEWABLE ENERGIES	Does the MRF have renewable energy systems such as photovoltaic or wind systems?	1	0	0	
			18	NATURAL LIGHTING	Does the MRF have natural light utilization systems such as translucent roofs, skylights, or clerestories?	1	0	0	
			19	HIGH-EFFICIENCY LIGHTING	Does the MRF have a high-efficiency lighting system such as LED and presence sensors?	1	0	0	
			20	THERMAL/ACOUSTIC INSULATION	Does the MRF have any thermal or acoustic insulation system?	1	0	0	
TECHNICAL OPERATIONAL	F	ASSOCIATION/COOPERATIVE AND WASTE PICKERS	21	PRODUCTIVITY	Is the MRF productive? (Consider 2.000 kg per waste picker as reference).	1	0	0	0,00
			22	ASSOCIATION/COOPERATIVE	Are the waste pickers organized by means of an association or cooperative?	1	0	0	
			23	ASSOCIATION/COOPERATIVE REGULARIZATION	Does the association or cooperative operating at the MRF have legal status, internal regulations, and board minutes?	1	0	0	
			24	CHILD LABOURS	Is there presence of child working at the MRF?	0	1	0	
			25	TECHNICAL GUIDANCE	Does the MRF have technical guidance (Ex: technician, technologist, or engineer)?	1	0	0	
			26	TRAINING AND CAPACITY BUILDING	Do the MRF waste pickers have semi-annual or annual training and capacity building?	1	0	0	
			27	INCLUSION OF AUTONOMOUS WASTE PICKERS	Does the association/cooperative operating at the unit have a program for the inclusion of autonomous waste pickers?	1	0	0	
	G	REGULARIZATION AND LICENSING	28	PROPERTY OWNERSHIP	Does the area designated for the MRF present documentary proof of ownership (registration, deed) and is there no documentary or judicial restriction?	1	0	0	
			29	BUSINESS LICENSE	Does the MRF have an busines licence?	1	0	0	
			30	DOCUMENTARY RESTRICTIONS	Does the association or cooperative have a session on the use of the shed and equipment?	1	0	0	
			31	ENVIRONMENTAL LICENSING	Does the MRF have an environmental license?	1	0	0	
			32	FIRE DEPARTMENT APPROVAL	Does the MRF present licensing with the Military Fire Department (MFD)?	1	0	0	
	H	PROTECTION	33	INSALUBRITY PARAMETERS	Does the MRF present any insalubrity parameter such as humidity, excessive heat, noise above recommended, excessive vibrations, or ergonomic problems?	0	1	0	
			34	STAFF UNIFORM	Are the collaborators adequately uniformed?	1	0	0	
			35	INDIVIDUAL PROTECTION EQUIPMENT (IPE's)	Do the waste pickers have the necessary individual protection equipment? (Ex: gloves, apron, safety glasses, and boots)?	1	0	0	
			36	COLLECTIVE PROTECTION EQUIPMENT (CPE's)	Does the MRF present collective protection equipment (extinguishers, warning signs, signaling on the equipment)?	1	0	0	
	I	SUPPORT INFRASTRUCTURE	37	ADMINISTRATIVE SECTOR	Does the MRF have an administrative sector?	1	0	0	
			38	KITCHEN OR CANTEEN	Does the MRF have a space destined for a refectory, kitchen, or cup?	1	0	0	
			39	SANITARY/DRESSING ROOMS	Does the MRF have male and female sanitary and dressing rooms?	1	0	0	
	J	MATERIALS AND EQUIPMENT	40	OFFICE SUPPLIES	Does the MRF have office supplies for daily use?	1	0	0	
			41	ADEQUATE EQUIPMENT	Does the MRF have sufficient quantity of equipment necessary for sorting and waste storage (conveyor belt, press, scale, forklift, moving carts for bales)?	1	0	0	
			42	EQUIPMENT CONSERVATION	Are the equipment in good state of conservation?	1	0	0	
	K	OPERATIONAL MONITORING	43	DATA ACESS	Are the results being passed on to the associates or cooperatives in a coherent manner?	1	0	0	
			44	RESIDUAL AND RECYCLING RATE	Is the rejection rate received by the MRF less than 30%? Do you know or monitor the rejection and recycling rates?	1	0	0	
			45	ATTENDANCE MONITORING	Does the MRF monitor the attendance of the waste pickers?	1	0	0	
SOCIOECONOMIC	L	ACCOUNTING/INCOME/BENEFITS	46	ACCOUNTING AND INVOICE CONTROL	Does the association have accounting support and control of tax invoices?	1	0	0	0,00
			47	ADEQUATE INCOME	Do the waste pickers receive a salary equal to or greater than 01 minimum wage?	1	0	0	
			48	AGREEMENTS	Does the MRF have any agreement, service provision contract, or reverse logistics contract?	1	0	0	
			49	QUALIFICATION SUPPORT	Do the waste pickers have access to any type of support for professional qualification or training?	1	0	0	
			50	LIFE INSURANCE	Do the waste pickers have life insurance?	1	0	0	
					TOTAL SCORE				0,00

CLASSIFICATION TABLE		SCORE
38 to 50 points	EXCELLENT	0,0
26 to 37 points	GOOD	
13 to 25 points	INSUFFICIENT	
0 to 12 points	POOR	

Figure 3 – Overview of the MRF-QI.

After applying the protocol to the MRF located within the studied planning unit, the results were organized in Microsoft Excel and subjected to descriptive statistical analysis. The analysis included minimum and maximum values, mean, standard deviation, and coefficient of variation. A sensitivity analysis was then performed to identify which protocol indicators influenced the final classification of the MRF the most. A univariate (one-way) approach was adopted, in which each indicator was individually reversed (yes to no, and vice versa), and the total score was recalculated. The resulting classification was subsequently compared to the original category (Poor, Insufficient, Good, or Excellent). For each indicator, the number of category changes was recorded, allowing the construction of a sensitivity ranking. Indicators associated with a higher frequency of category changes were considered more influential. These indicators represent the protocol components with the greatest impact on the final assessment, therefore warranting priority consideration in future interventions or potential protocol refinements.

Planning unit selected for application of the MRF-QI protocol

The planning unit selected for the application of the MRF-QI protocol encompassed 28 municipalities in the Paraná III hydrographic basin, located in the western mesoregion of the State of Paraná, between the coordinates 24°01' S and 25°35' S and 53°26' W and 54°37' W (Figure 4), covering an area of approximately 8,000 km² and containing 34 MRF.

This planning unit was selected due to the accessibility of operational data from the MRF and the interest of key stakeholders, particularly managers of the Solid Waste Management Program, in improving waste management efficiency. In addition, as human activities within a watershed directly affect the quality of receiving water bodies (SEMA, 2013), adopting the watershed as a planning unit supports a better integrated and sustainable approach to resource management, including the appropriate handling of generated waste.

The Solid Waste Management Program implemented in western Paraná includes investments in infrastructure and technical-social training. Municipalities contribute by providing land, warehouse facilities, and a waste management technician, ensuring that revenues from the sale of recyclable materials are fully managed and retained by cooperative members. Consequently, the socioeconomic category in this study focused exclusively on accounting-related aspects, such as income and benefits received by cooperative members. In the planning unit where the protocol was applied (western Paraná), no direct municipal subsidies were provided for the sale of recyclable materials.

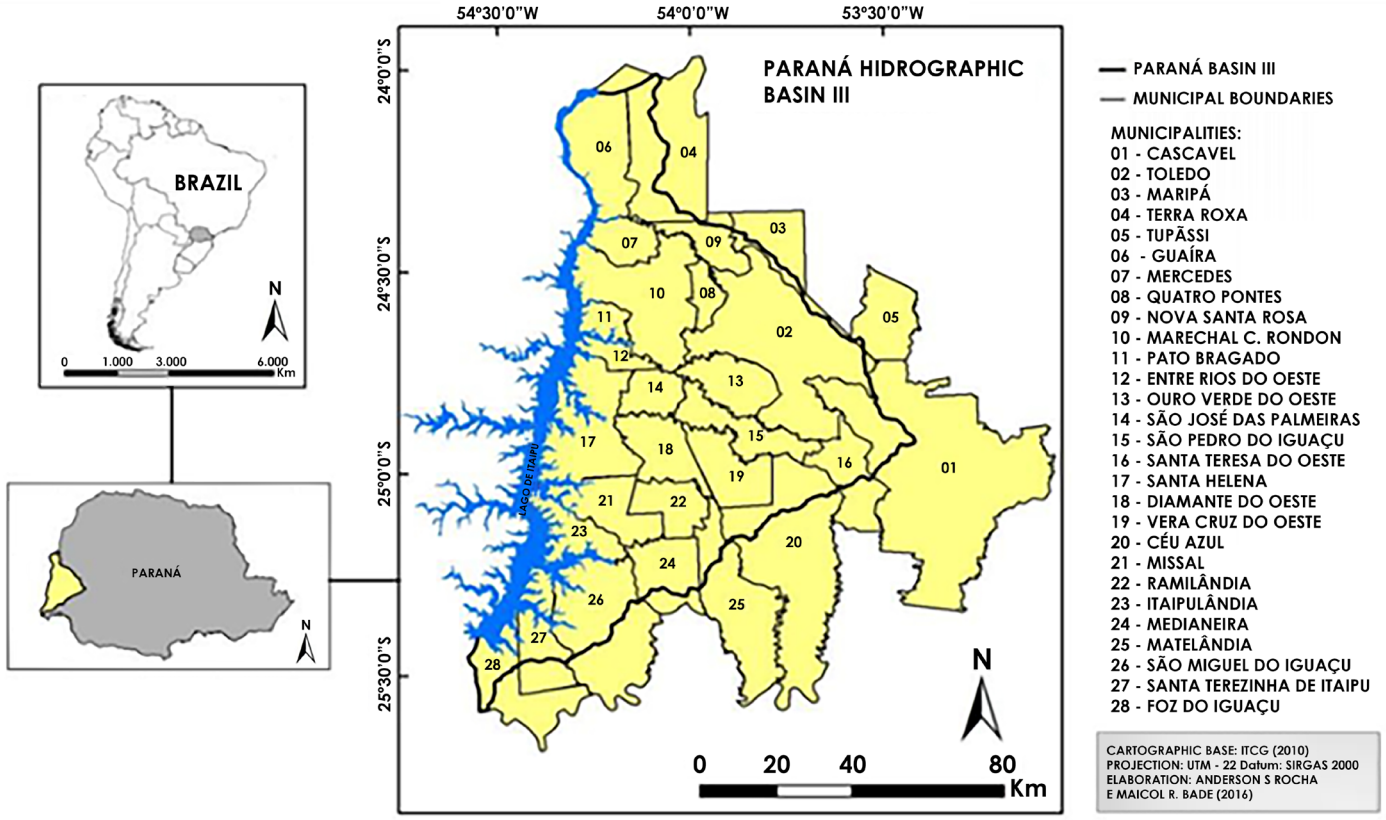

Figure 4 – Municipalities located in the Paraná III Hydrographic Basin of the planning unit selected for the application of the MRF-QI protocol.
Source: Rocha et al. (2016).

Results and Discussion

Application of the MRF-QI

The MRFs were identified by numbers from 01 to 34 (Table 2) in accordance with confidentiality criteria, following the descending order of MRF-QI score. Detailed results of the evaluation of each MRF are available in the supplementary material. The application of the protocol in several facilities established a basis for comparison, demonstrating the importance of the multidimensional approach for an objective assessment of the current MRF scenario, also helping to identify aspects with potential for future improvement interventions.

Out of the 34 MRFs evaluated using the MRF-QI protocol, 44% were classified as having *excellent* quality, meeting between 76 and 96% of the indicators. The remaining 56% were classified as *good*, with compliance ranging from 56 to 74%. Average efficiencies of 85, 77, 59, and 57% were observed for the technical-operational, physical, environmental, and socioeconomic categories, respectively. These results indicate that, despite an adequate overall infrastructure, the evaluated MRFs still require improvements related to occupational health, environmental sustainability, and social development of cooperative members. Nevertheless, all facilities achieved high-quality index values, with an overall average efficiency (AE) of 75%, corresponding to more than 28 of the 50 possible points. This performance suggests that MRF management, particularly among facilities classified as *excellent*, is largely aligned with best practices in the sector and has been effective in managing recyclable waste.

MRFs 01 and 02 achieved the highest scores, with 48 points each, demonstrating that high-quality standards can be attained across all evaluated categories. In contrast, facilities scoring between 28 and 37 points (MRFs 16 to 34) still exhibit room for improvement, particularly in indicators that received no score. A detailed analysis of the 15 MRFs classified as *excellent* showed that, for the physical dimension, MRFs 01, 02, 03, 05, 06, and 11, representing 40% of the units in this category, achieved the maximum score of 10 points. This result indicates that these facilities offer an adequate location, secure conditions, and well-maintained infrastructure for recyclable waste management (Figure 5). The remaining MRFs scored between 7 and 9 points, mainly due to the absence of scores for ventilation and surveillance parameters. These findings highlight opportunities for continuous improvement in the physical conditions of these facilities.

Table 2 – Results of applying the MRF-QI protocol in the 34 selected facilities.

MRF	Categories				Points	Classification
	Physical	Environmental	Technical-operational	Socioeconomic		
MRF 01	10	10	24	4	48	Excellent
MRF 02	10	9	24	5	48	Excellent
MRF 03	10	7	24	5	46	Excellent
MRF 04	9	8	25	3	45	Excellent
MRF 05	10	7	23	3	43	Excellent
MRF 06	10	5	23	4	42	Excellent
MRF 07	9	9	20	3	41	Excellent
MRF 08	8	7	22	3	40	Excellent
MRF 09	7	7	23	3	40	Excellent
MRF 10	8	7	21	3	39	Excellent
MRF 11	10	5	21	3	39	Excellent
MRF 12	9	6	21	3	39	Excellent
MRF 13	8	6	22	2	38	Excellent
MRF 14	8	7	21	2	38	Excellent
MRF 15	7	6	22	3	38	Excellent
MRF 16	6	5	23	3	37	Good
MRF 17	9	4	22	2	37	Good
MRF 18	9	7	18	3	37	Good
MRF 19	7	5	21	3	36	Good
MRF 20	8	6	20	2	36	Good
MRF 21	6	7	20	3	36	Good
MRF 22	9	5	18	3	35	Good
MRF 23	8	4	20	3	35	Good
MRF 24	7	3	21	3	34	Good
MRF 25	7	7	17	3	34	Good
MRF 26	8	6	17	2	33	Good
MRF 27	8	4	19	2	33	Good
MRF 28	9	3	18	1	31	Good
MRF 29	5	5	19	2	31	Good
MRF 30	4	3	20	3	30	Good
MRF 31	3	5	19	3	30	Good
MRF 32	4	6	17	2	29	Good
MRF 33	5	4	16	3	28	Good
MRF 34	7	4	15	2	28	Good
MINIMUM	3	3	15	1	28	
MAXIMUM	10	10	25	5	48	
AVERAGE	8	6	20	3	37	
SD	2	2	3	1	5	
CV	24%	30%	12%	29%	15%	
$AE_{(\%)}$	77%	59%	85%	57%	74%	

MRF: material recycling facility; SD: standard deviation; CV: coefficient of variation; $AE_{(\%)}$: Average efficiency, measured by the percentage of average points obtained in relation to the maximum possible score (50 points).

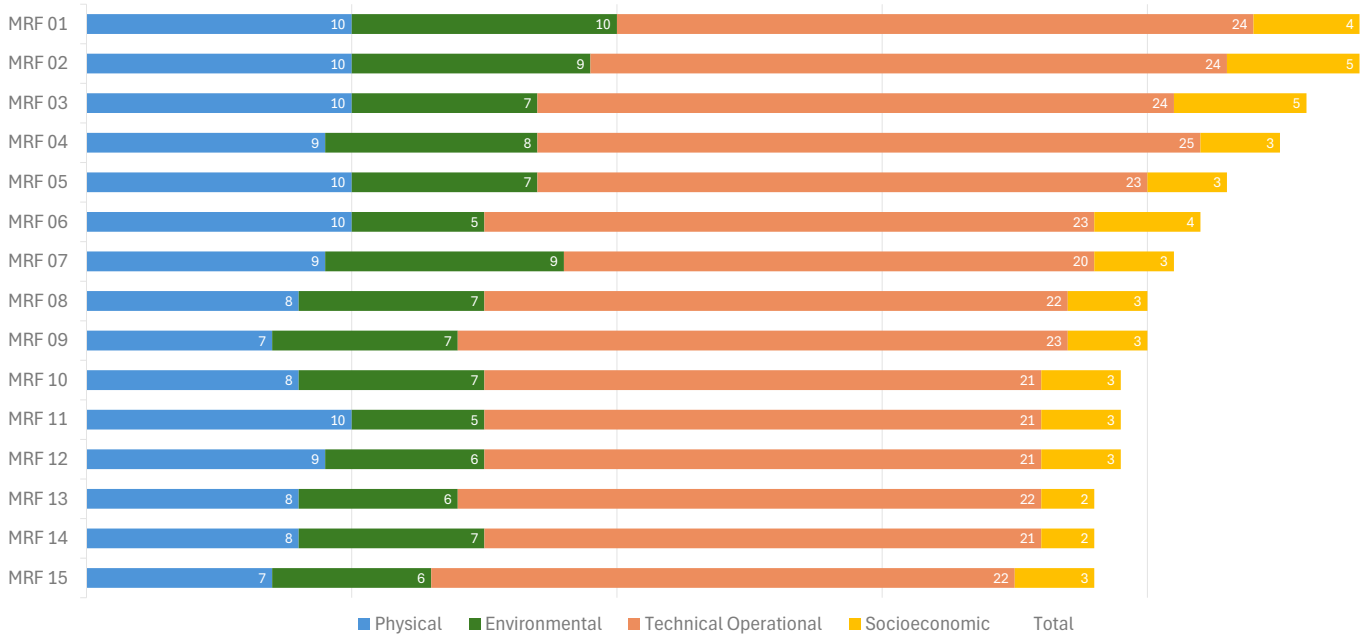

Figure 5 – MRF score with MRF-QI classified as excellent.

In the environmental category, only MRF 01 achieved the maximum score of 10 points. The other facilities scored zero, particularly due to indicators related to sustainable resource use. Renewable energy, natural lighting, and high-efficiency lighting were the least frequently observed parameters, indicating clear opportunities for future investments to improve environmental performance. In the technical-operational category, MRF 04 achieved the highest score, with 25 points, followed by MRFs 01, 02, and 03, each with 24 points. These high scores are mainly associated with legal compliance, the availability and adequate maintenance of equipment and materials for workers, and the provision of staff training. Together, these factors contribute to increased operational efficiency, enhanced service quality, and more effective resource utilization. In contrast, MRFs 07, 10, 11, 12, and 14 obtained the lowest scores, ranging from 20 to 21 points. This performance is primarily linked to deficiencies in the inclusion of independent waste pickers, the absence of operating licenses, and noncompliance with hazardous work requirements.

In the socioeconomic category, only MRFs 02 and 03 achieved the maximum score of 5 points. This result reflects effective accounting control and positive relationships with waste pickers, including adequate income levels and access to life insurance. The remaining facilities scored between 2 and 4 points, indicating the need for improvements in accounting practices and in the provision of income-related benefits and social rights. In the western region of Paraná, where the protocol was implemented, the Solid Waste Management Program provides investments in infrastructure, technical and social training. Municipalities contribute by supplying land, warehouse facilities, and a waste management technician, while revenues from recyclable sales are fully managed by cooperative members. As a result, the socioeconomic category focused exclusively on accounting aspects, including income and benefits for cooperative members, since no direct municipal subsidies are provided for the sale of recyclables in this planning unit.

Regarding the detailed results of the 19 MRFs classified as *good*, with scores ranging from 26 to 37 points out of a maximum of 50 in the MRG-QI (Figure 6), it was observed that, although these scores are considered satisfactory (above 25 points), none of the facilities achieved the maximum rating across the four evaluated categories.

In the physical category, MRFs classified as having *good* performance achieved anaverage score of 7 points. Facilities 29, 30, 31, 32, and 33 recorded the lowest scores, ranging from 3 to 5 points (out of 10). These results were primarily attributed to inadequate site locations, limited infrastructure, and the absence of accessibility and surveillance systems. In contrast, MRFs 17, 18, 22, and 28 showed the best performances, failing to score in only one of the evaluated parameters.

The environmental category presented the weakest performance among all categories, with an overall average score of 5 points. Only six MRFs (18, 20, 21, 25, 26, and 32) out of the 19 evaluated achieved scores above 5 (out of 10). The remaining units scored between 3 and 5 points, with MRFs 24 and 30 presenting the lowest performance, scoring only 3 points. These results indicate deficiencies in pollutant control and natural resource management. Parameters related to odor control, the presence of disease vectors, and the use of renewable energy sources for lighting were not met by most units and therefore were identified as priority areas for investment.

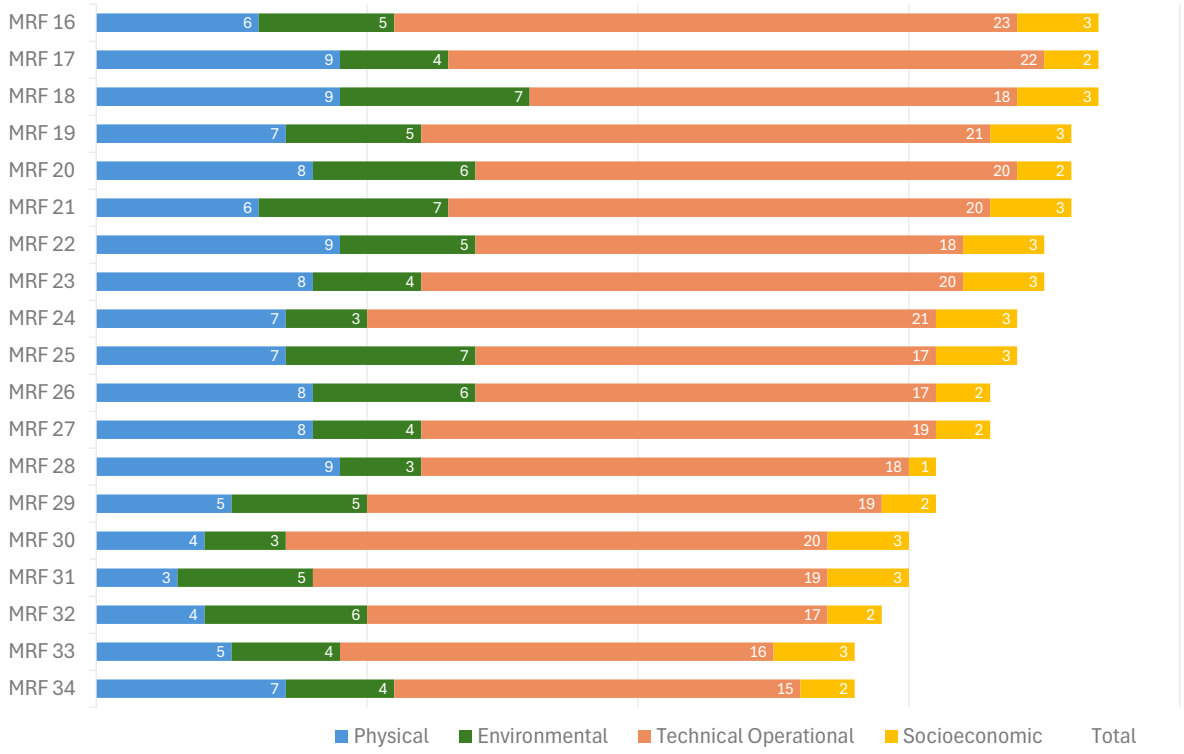

Figure 6 – MRF score with MRF-QI classified as good.

The technical-operational category showed the strongest overall performance, with an average score of 19 points out of a possible 25. MRFs 25, 26, 32, 33, and 34 obtained the lowest scores in this category, ranging from 15 to 17 points. These lower values were mainly associated with the absence of life insurance coverage and limited support for education and professional qualifications. In contrast, MRFs 16 and 17 achieved the highest scores, with 23 and 22 points, respectively.

The socioeconomic category achieved an average score of 3 points (out of a maximum of 5), with eight units scoring below this value. MRF 28 showed the lowest performance in this category, scoring a single point, primarily due to the absence of accounting and invoice control systems, formal agreements, and life insurance.

The application of the MRF-QI protocol across the 34 units of the Itaipu Waste Management Program enabled a comprehensive assessment of unit performance based on physical, environmental, technical-operational, and socioeconomic indicators. Overall performance levels ranged from *good to excellent*, indicating that the management practices adopted, particularly in units classified as *excellent*, are aligned with the best practices in the industry and demonstrate effective management of incoming recyclable materials. The use of multiple indicators allowed for the identification of both structural challenges and operational opportunities across the evaluated units.

Furthermore, the protocol proved to be a strategic tool for identifying improvement priorities and supporting planning and decision-making processes in MRF management. Its application enables periodic assessments, continuous performance monitoring, and benchmarking among units by identifying best practices. By encouraging the exchange of experiences and knowledge among MRFs, the protocol facilitates the dissemination and replication of effective management practices in other contexts. Facilities with *excellent* performance can also serve as reference models, providing incentives and guidance for facilities seeking to improve their operational quality.

Relevance of an assessment protocol as a tool for monitoring the efficiency of the MRFs

The absence of standardized and comprehensive tools capable of directly assessing the performance of the MRFs, while distinguishing them from evaluations of municipal selective collection systems, remains a persistent challenge in solid waste management. Previous studies have addressed this issue from different perspectives. De Sá et al. (2023) developed a sustainability indicator matrix applied in João Pessoa, Brazil, incorporating variables such as service coverage, population participation, selective collection costs, and the mass of waste collected. Costa and Barbosa (2021) proposed a questionnaire focused on the quality of life of recyclable waste pickers, addressing aspects related to leisure, safety, income, and transportation. In turn, Besen et al. (2017) proposed 21 relative percentage indicators to assess MRF sustainability, grouped into five dimensions: legal and institutional, socioeconomic, organizational, operational efficiency, and working conditions, health, and occupational safety.

By providing a clear quality metric based on a point-scale system combined with binary (yes/no) responses, the protocol developed in this study enables both simplified and detailed diagnoses of current facility conditions. This approach supports the identification of critical weaknesses, such as inadequate infrastructure, unfavorable locations, and low process efficiency, helping to directly target corrective actions. Consequently, the protocol contributes to improvements in selective collection coverage and recyclable material recovery rates. An additional strength of the proposed tool lies in its potential to standardize management practices across different regional contexts. Its application in western Paraná demonstrates the feasibility of adopting common evaluation criteria for comparing MRFs and generating evidence to support more coordinated actions at municipal and state level. Moreover, the protocol serves as a management support tool by facilitating the sharing of experiences and the dissemination of the best practices among facilities. When combined with continuous data analysis, this feedback process can enhance MRF performance and facilitate the replication of successful, context-adaptable solutions.

The findings of this study are expected to encourage continuous monitoring and the implementation of policies and protocols aimed at improving MRF quality. The application of the protocol across 34 facilities confirmed the effectiveness of a multidimensional approach to performance evaluation. This approach provides a clear overview of current operating conditions and identifies priority areas for intervention. Actions derived from these results can strengthen efficiency, sustainability, and social responsibility indicators, while also optimizing MRF operations. By linking technical-operational performance with socioeconomic dimensions, the protocol supports a broader interpretation of recyclable waste valorization. This perspective goes beyond purely technical assessments and explicitly recognizes the social role of MRFs. As such, tools of this nature are essential in the advancement of more efficient and inclusive waste management models aligned with circular economy principles and environmental sustainability.

A statistical sensitivity analysis was conducted for the 50 parameters included in the MRF-QI. Based on the number of category changes observed when each parameter was inverted (i.e., scored versus not scored), it was possible to estimate the influence of individual parameters on facility classification (*Poor, Insufficient, Good, or Excellent*). Parameters were classified as *highly sensitive* when five category changes occurred, of *high influence* with four changes, and of *lower influence* when one to three changes were observed (Figure 7).

The parameters *accessibility* and *equipment conservation* showed the greatest sensitivity. Therefore, these were revealed to be the most critical parameters of the MRF-QI, with five changes, even with equal weights for all parameters, since they may be closer to the classification boundaries (12–13, 25–26, 37–38). Therefore, these results indicate that by improving the performance of these two parameters, several cooperatives can have a better evaluation of their performance and be classified in a higher category.

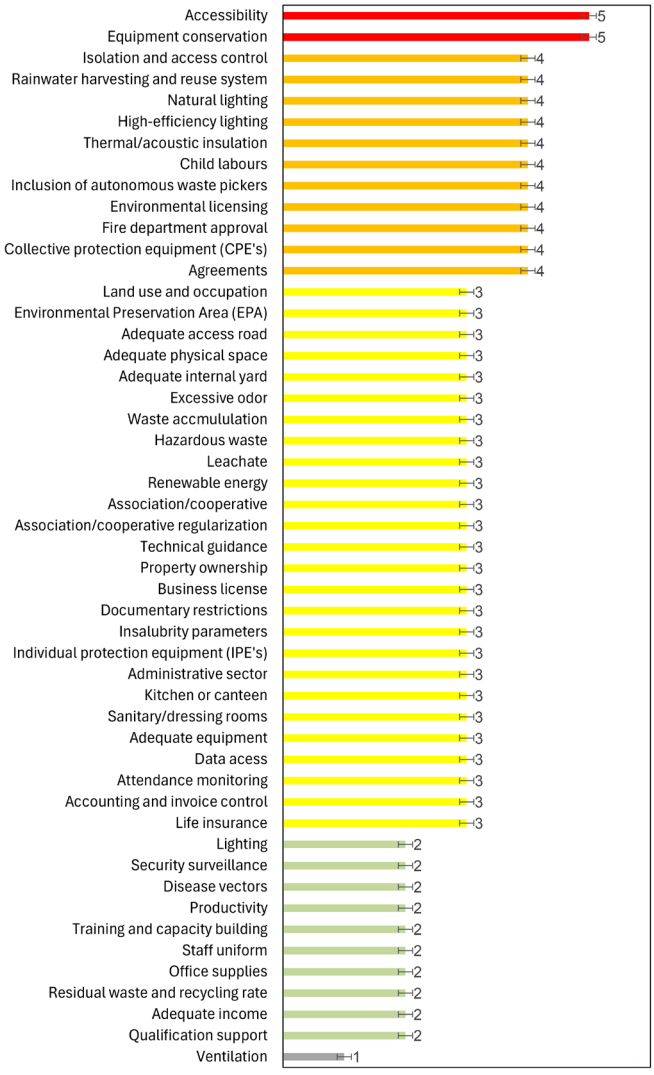

Figure 7 – Ranking of the MRF-QI indicators classified by the amount of change in sensitivity analysis.

Furthermore, eleven parameters resulted in *high influence*, with four changes each. In general, these parameters evaluated access control, lighting, thermal insulation, environmental licensing, rainwater harvesting, personal protective equipment, child labour, and the formalization of agreements. Although not as influential as the first two parameters mentioned, this second group of indicators resulted in high influence in the sensitivity analysis; that is, they are essential for the formulation of intervention and training policies in MRFs. The remaining 37 parameters were classified as having the least influence according to the sensitivity analysis, revealing that changing the yes/no response in the MRF-QI protocol would result in the least impact on changes in MRF categories. Even so, it should be noted that individual improvements in the evaluated parameters can have a significant

impact on the legislation, performance, and environmental health of MRFs, and specific analyses should be applied accordingly.

Conclusions

A new protocol (MRF-QI) was developed to evaluate the quality of material recovery facilities by integrating qualitative and quantitative indicators across physical, environmental, technical-operational, and socioeconomic dimensions. The protocol was applied to 34 MRFs in the Paraná III Hydrographic Basin, where 44% of the units demonstrated an *excellent* performance, and 56% achieved a *good* performance. Average efficiencies of 85, 77, 59, and 57% were observed for the technical-operational, physical, environmental, and socioeconomic categories, respectively. These results demonstrate that, despite having adequate infrastructure, MRFs still require improvements in occupational health, environmental sustainability, and the social development of cooperative members. The protocol proved to be efficient and standardized, enabling the identification of operational differences and supporting continuous improvement. Its periodic application can help track MRF performance, guide management decisions, and promote the dissemination of best practices. The sensitivity analysis identified thirteen of the fifty evaluated parameters as the most influential, offering clear priorities for targeted interventions. Future research should also apply the protocol to other regions of Paraná and Brazil with different investment contexts and assess how implemented improvements influence the potential identified by the protocol. Such efforts will support the sustainable development of both the facilities and the surrounding regions.

Authors' Contributions

Turmina Junior, A.: formal analysis; investigation; writing; **Correia**, J. E.: conceptualization; **Prates**, K. V. M. C.: conceptualization; writing; **Bassani**, F.: conceptualization; writing; **Pereira**, L. M. S.: writing; **Edwiges**, T.: supervision; writing.

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