

Article

Indicator Matrix for Sustainable Solid Waste Management in Rural Communities in the Western Amazon

Benone Otávio Souza de Oliveira¹, Gabriel dos Anjos Guimarães², Romário Martins Pereira³,
Miqueias Lima Duarte⁴, Renato Francisco da Silva Souza⁵, Rodrigo Couto Alves⁶

¹ Ph.D. in Environmental Sciences. Federal University of Amazonas. ORCID: 0000-0002-5404-0409. E-mail: benone@ufam.edu.br

² Master's in Science and Technology for Amazonian Resources. Federal University of Pará. ORCID: 0000-0002-4491-9727. E-mail: gaguimaraes09@gmail.com

³ Master's Degree in Environmental Sciences. Federal University of Amazonas. ORCID: 0000-0002-4950-5478. E-mail: romampereira@gmail.com

⁴ Ph.D. in Environmental Sciences. Federal University of Amazonas. ORCID: 0000-0001-8232-4655. E-mail: miqueiaseng@hotmail.com

⁵ Ph.D. in Soil Science. Federal University of Amazonas. ORCID: 0000-0001-8213-1722. E-mail: renatofssouz@gmail.com

⁶ Ph.D. and M.S. in Environmental Sciences and Sustainability. Federal University of Amazonas. ORCID: 0000-0002-7452-9455. E-mail: rcouto@ufam.edu.br

ABSTRACT

The excessive production of solid waste today is one of the major challenges for municipal managers, particularly regarding environmental and health issues in urban and rural areas. This scenario is particularly pronounced in isolated or rural communities due to lower population density, logistical challenges, and a lack of sanitation infrastructure, resulting in negative impacts on the social, economic, and health aspects of community life. The study sought to identify methods of final disposal for solid waste in five rural communities in Humaitá, as well as to develop and apply a matrix of indicators for the sustainable management of solid waste produced in these communities. The methodological process included a literature review, on-site visits, photographic documentation, visual assessment to describe waste disposal methods, qualitative and quantitative characterization of the solid waste generated in the communities, data collection from public agencies and waste management companies in the municipality of Humaitá, and the application and analysis of eight sustainability indicators. The results indicated that the burning of inorganic solid waste in open-air trenches is the most common method used by community members. A significant difference was observed among the analyzed sites, with a predominance of organic material, followed by plastic film. The indicator matrix revealed that the stages in all communities were similar in relation to the management indicators. The information generated by this study may assist in improving solid waste management in rural communities of the Western Amazon, serving as a basis for the proper development of an integrated solid waste management plan.

Keywords: environmental problems; environmental indicators; sustainable management; rural area; Amazon region.

Introduction

In recent years, solid waste generation has increased at an alarming rate, driven by population growth and rapid urbanization, which intensify the demand for goods and services (Silva et al. 2019; Olay-Romero et al. 2020; Morais et al. 2021; Devendran et al. 2023). Furthermore, the growing consumption of disposable products, the short lifespan of many products, and the increase in the population's purchasing power have exacerbated this situation. These combined factors are not only significantly impacting the environment—through soil, water, and air pollution—but also posing challenges for waste management, which now requires more innovative and sustainable solutions to reduce environmental damage and promote more balanced development (Guimarães et al. 2023; Guimarães et al. 2024).

In this context, Souza et al. (2019) highlight that, in addition to the alarming increase in solid waste generation, the composition of this waste is becoming increasingly complex, involving a wider variety of materials, many of which are difficult to recycle or treat. This global scenario poses a major challenge, not only due to the growing volume of waste but also because of the diversity of chemicals and industrial products that can cause adverse environmental impacts. As a result, both the environment and the population's quality of life



Submitted: 14/11/2025



Accepted: 27/03/2026



Publication: 18/06/2026



are being significantly affected, with consequences that include ecosystem degradation as well as risks to public health (Oliveira et al. 2016; Souza et al. 2019; Guimarães et al. 2024).

In light of the significant challenges faced by Brazilian municipalities in solid waste management, the federal government enacted Decree No. 10,936 in 2022, which regulates the National Solid Waste Policy, established by Law No. 12,305/2010 (Brazil 2010). This decree establishes principles, guidelines, objectives, and essential instruments for the implementation of technological innovations in both urban and rural solid waste management, aiming to improve the efficiency and sustainability of these processes (Oliveira et al. 2022a; Silva et al. 2023).

In Brazil, according to the National Sanitation Information System (SNIS), the country produced approximately 66.6 million tons of municipal solid waste in 2020. Furthermore, it is noteworthy that most Brazilian municipalities have solid waste collection service coverage exceeding 90% (SNIS 2022). However, when looking at rural communities, it becomes evident that 18.3 million inhabitants lack access to direct waste collection, highlighting the need to include these populations in waste management planning across Brazilian municipalities (SNIS 2022).

In this context, rural communities face significant changes resulting from inadequate solid waste management, exacerbating social, economic, environmental, and public health problems (Lima & Paulo 2018; Pereira & Fernandino 2019; Jucá et al. 2020; Castro et al. 2020; Guimarães et al. 2023; Guimarães et al. 2024).

In light of the above, sustainability indicators aim to determine whether the system is progressing or regressing (Silva et al. 2023). In this context, the indicators applied in solid waste management contribute to the structuring and formulation of public policies, simplify decision-making, promote a better understanding of environmental systems, and more (Pereira et al. 2018; Silva & Pessali 2018; Souza et al. 2019).

To this end, selecting indicators is no easy task, as it requires integrating different dimensions of sustainability to enable their interpretation, situational analysis, and assessment of future prospects (Santiago & Dias 2012; Castro et al. 2015; Cervantes et al. 2018; Barros & Silveira 2019).

Therefore, given the organizational fragility faced by most municipalities in the Amazon region regarding solid waste management in rural areas, this study aimed to describe the final disposal methods for solid waste in five rural communities located within the Buffer Zone of the Humaitá National Forest, and to identify, develop, and apply a matrix of indicators aimed at the sustainable management of solid waste and the improvement of quality of life.

Materials and Methods

Study Area

The municipality of Humaitá covers a large area of 33,072 km² and has an estimated population of 57,473 inhabitants, of whom approximately 31% live in rural areas (IBGE 2023). In this context, the study was conducted in five rural communities within the Buffer Zone of the Humaitá National Forest (Flona Humaitá): Flechal, Ilha do Tambaqui, Mirari, Paraisinho, and Paraíso Grande (Figure 1). Information on these communities is described in Table 1.

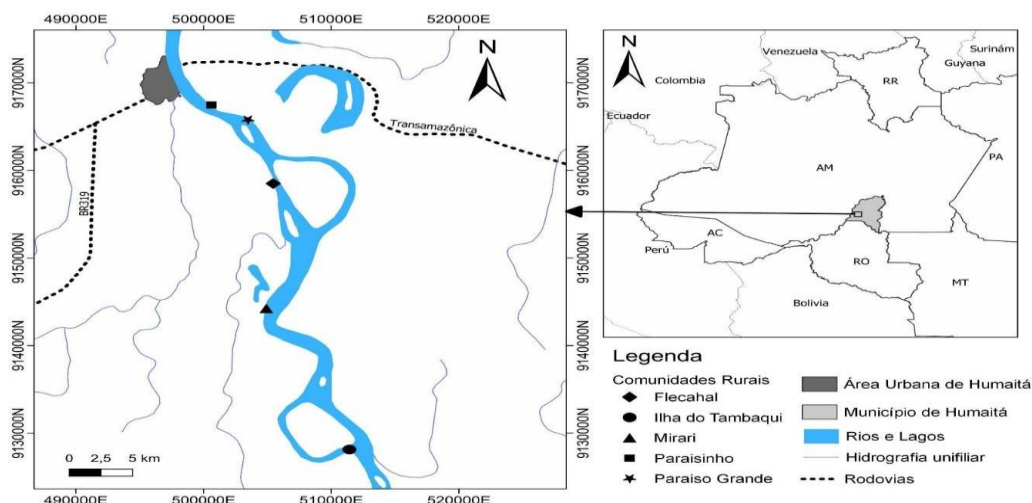


Figure 1. Location Map of the studied communities that make up the Buffer Zone of Flona Humaitá. Source: The authors (2026).



The communities of Flechal, Mirari, and Ilha do Tambaqui are located on the left bank of the Madeira River, at distances of 13 km, 26 km, and 44 km, respectively, from the municipality of Humaitá. On the other hand, the communities of Paraíso Grande and Paraíso Grande are located on the right bank of the Madeira River, approximately 3.5 km and 7 km away, respectively, from the municipality of Humaitá.

Table 1. Location and demographic data of the communities mentioned in this study. (*= Not recorded)

Community	Geographic Coordinates	Houses	Population
Flechal	7°36'44.95" S, 62°57'2.72" W	13	70
Mirari	7°44'30.13" S, 62°57'19.20" W	24	105
Tambaqui Island	7°53'14.93" S, 62°53'46.81" W	18	55
Paraíso Grande	7°31'53.35" S, 62°59'40.28" W	NR*	100
Paraíso Grande	7°32'48.53" S, 62°58'6.09" W	NR	150

Source: The authors (2026).

According to the Koppen climate classification system, the region corresponds to the humid tropical climate, characterized by a prolonged rainy season and a short dry season (AM), an average annual temperature ranging from 25 to 27°C, an average annual precipitation of 2,000 mm, and relative atmospheric humidity between 85 and 90% (Alvares et al. 2013).

Regarding solid waste management, the municipality of Humaitá complies with Federal Law No. 12,305 of August 2, 2010, which established the National Solid Waste Policy regarding the development of the municipal integrated solid waste management plan.

However, the stages of waste management in the municipality are limited to the collection process, which covers the entire urban area of the municipality, totaling 15 km², along with transportation and disposal at an open-air landfill located approximately 10 km from the urban area (Oliveira & Medeiros 2020; Oliveira et al. 2022a).

Currently, the collection process in the urban area is conducted door-to-door using 5 m³ compactor trucks, with a frequency of 6 times per week in all residential neighborhoods and 7 times per week in the central area of the municipality (Oliveira & Medeiros 2020). In contrast, it is noted that the collection process does not serve rural areas (communities, districts, settlements, indigenous reserves) with river access (Oliveira et al. 2022a).

Therefore, the research was conducted in three stages: In the first stage, an exploratory and descriptive bibliometric analysis of the entire legal framework regarding solid waste management was carried out. The second stage consisted of field research, involving *on-site* visits to communities and municipal government agencies to characterize the waste in the communities. In the remaining stages, a qualitative and quantitative characterization of the solid waste generated in the communities was performed, along with the application of the sustainability indicator matrix.

Qualitative and quantitative characterization of solid waste

The qualitative and quantitative characterization of solid waste was conducted in five rural communities within the Buffer Zone of the Humaitá National Forest (Flona Humaitá): Flechal, Ilha do Tambaqui, Mirari, Paraíso Grande, and Paraíso Grande, with a total estimated population of 480 inhabitants.

In this context, the characterization of solid waste in the communities was carried out in accordance with procedures established by Cempre (2018), which recommends the sorting of all generated waste when the amount of waste produced is less than 1.5 tons. Therefore, data collection in the communities involved two sampling periods (dry and rainy seasons) between 2022 and 2023, with three repetitions, totaling 15 samples.

In each sampling, waste collection was conducted manually door-to-door at community members' residences; the waste was then transported to a suitable location, where the plastic bags containing the waste were opened for analysis, and the waste was subsequently weighed to determine its percentage relative to the total collected sample.

Next, the specific weight of the material was calculated using a graduated cylinder with a defined volume of 60 liters (0.06 m³) and a digital industrial scale with a capacity of 50 kg (DPB-50KGX10G RAMUZA). Furthermore, the result was obtained by calculating the ratio of the sample mass (kg) to the total sample volume (m³).

Daily per capita waste generation in the communities was determined based on the ratio of the total mass collected to the number of community residents (Bernardes & Gunther 2014).



The samples were classified into predetermined categories, namely: Organic matter, PET, Paper/Cardboard, Rigid Plastic, Plastic Film, Metals, Glass, Long-Life Items, Fabric/Leather, and others (Styrofoam, rubber, medical waste, wood, coal, batteries).

Statistical Analysis

After classifying the predominant categories, the data were subjected to descriptive statistical analysis, as well as analysis of variance (ANOVA) and Tukey's test (5% significance level). The analysis was conducted as a 5x3 factorial design, taking into account the five collection sites and the three periods during which the collections were carried out. The statistical analysis was performed using the multcomp package in the R software (R Core Team 2024).

Indicator Matrix

To construct a model for adequate solid waste management in communities, the indicator matrix proposed by Castro et al. (2015) was adapted, taking into account the municipality's specific characteristics and the requirements of the PNRS. In this context, eight indicators were described that encompass the dimensions of sustainability:

- Existence or absence of a Municipal Plan for Integrated Solid Waste Management, covering waste in rural areas;
- Information made available to the general public regarding solid waste management;
- Existence of channels for public participation in the decision-making process regarding solid waste management in urban and rural areas;
- Government support for the waste management chain;
- Solid waste collection in rural communities;
- Disposal of solid waste in rural communities;
- Utilization of organic waste;
- Projects to prevent and reduce environmental impacts and health risks to the rural population from waste management activities.

In this context, the indicators address different aspects of solid waste management in both urban and rural areas. The first indicator assesses the existence of a Municipal Plan for Integrated Solid Waste Management specifically focused on rural areas. Next, the second indicator analyzes the population's access to relevant information regarding this management. The third indicator refers to the existence of channels that enable public participation in the decision-making process for waste management, covering both urban and rural areas. Furthermore, the fourth indicator examines the support provided by public authorities throughout the waste management chain. The subsequent indicators focus on practical aspects, such as the collection process (fifth indicator) and waste disposal (sixth indicator) in rural communities, as well as the utilization of organic waste (seventh indicator). Finally, the eighth indicator evaluates specific projects aimed at preventing and reducing environmental impacts and health risks to the rural population resulting from waste management activities.

In the scientific literature, a lack of reliable data from rural communities was observed, which necessitated a shift from a qualitative approach to a quantitative one, allowing for the final summation of the results for each indicator, as well as a comparison with an ideal scenario. Thus, using a *Likert* scale, the indicators will be measured on a five-point scale, as described in Table 2.

Table 2. Classification Levels of Rural Solid Waste Management Indicators.

Stage	Symbols	Classification Value
Ideal Stage	EI	2
Favorable Stage	EF	1
Attention Stage	EA	0
Unfavorable Stage	ED	-1
Critical Stage	EC	-2

Source: The authors (2026).



Results and Discussion

In the context of solid waste management in the rural communities of Flechal, Ilha do Tambaqui, Mirari, Paraíso Grande, and Paraíso Grande, located in the Buffer Zone of the Humaitá National Forest (Flona Humaitá), the most common practice among community members is the burning of inorganic solid waste in open-air pits. In addition, organic waste is frequently used as fertilizer or to feed animals in local backyards. This management approach reflects a common reality in rural communities of the Amazon, where the lack of infrastructure, incentives, awareness, and adequate environmental enforcement contributes to the persistence of these burning practices in the region (Guimarães et al. 2023; Guimarães et al. 2024). On the other hand, the use of organic waste as fertilizer or animal feed in local backyards is of extreme importance (Carneiro et al. 2024), as it promotes sustainable waste management practices, improves soil fertility, reduces agricultural and livestock production costs, and strengthens the autonomy of rural communities by utilizing available resources efficiently and economically (Palansooriya et al. 2023).

The results regarding solid waste disposal in communities within the Humaitá National Forest Buffer Zone corroborate the national scenario, which shows a high frequency of solid waste burning exceeding 60% in rural areas without protective measures (Lima & Paulo 2018; Fidelis-Medeiros et al. 2020; Caiado et al. 2021; Lima et al. 2021). Furthermore, the method of household solid waste disposal used by community members poses a significant risk to public health and the environment (Fidelis-Medeiros et al. 2020; Lima et al. 2021; Bezerra & Wankler 2023; Guimarães et al. 2023; Guimarães et al. 2024).

Table 3 shows the qualitative and quantitative results regarding household solid waste in the studied communities. The waste generated annually in the communities of Flechal, Mirari, Ilha do Tambaqui, Paraíso Grande, and Paraíso Grande reached approximately 4.04, 1.48, 3.91, 7.85, and 3.86 tons, respectively, based on the studies by Oliveira et al. (2022a), the urban area of Humaitá generated 14.83 t_{day⁻¹} of MSW (5,412 t_{year⁻¹}); therefore, the implementation of regular collection in the studied communities would represent a 0.4% annual increase in the amount collected and in the disposal of waste at the municipal landfill.



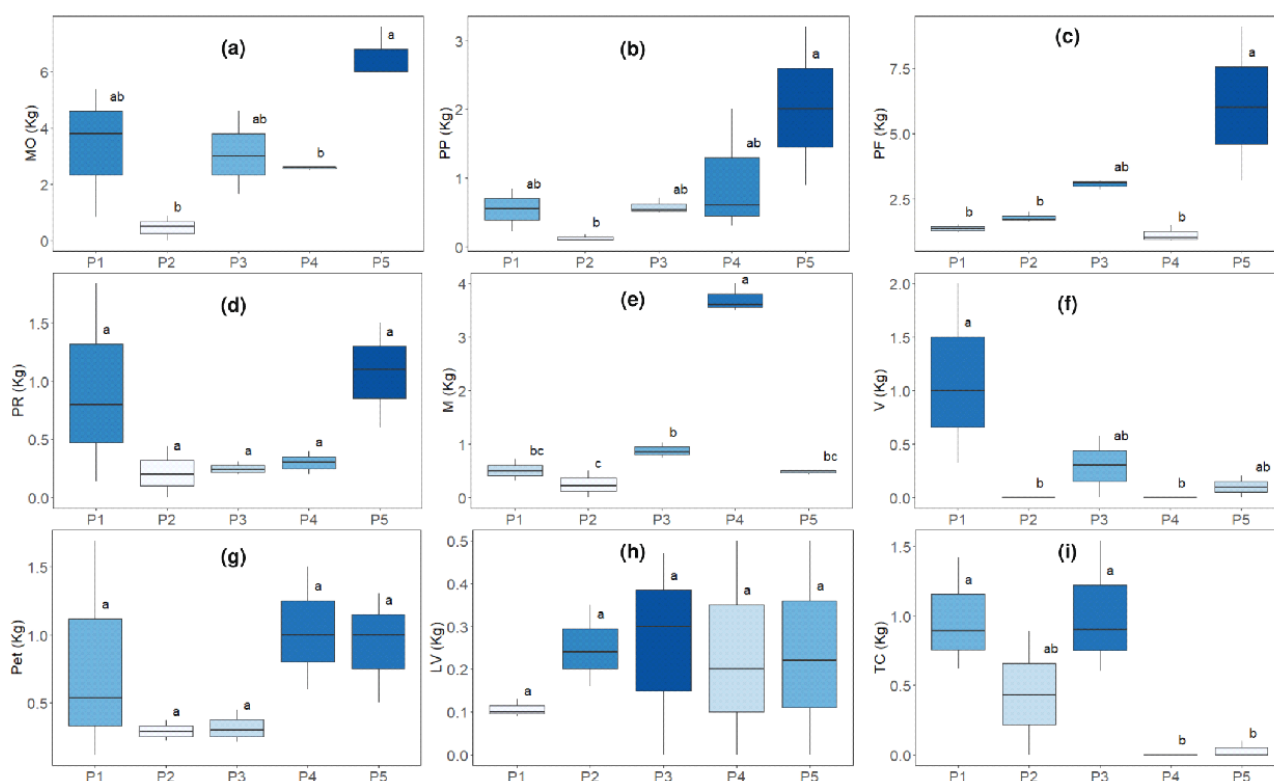
Table 3. Gravimetric composition of solid waste in rural communities in the municipality of Humaitá, Amazonas

Resíduo	Flechal			Mirari			Ilha do Tambaqui			Paraíso Grande			Paraísoinho		
	Média	DP		Average	SD		Average	DP		Average	DP		Average	DP	
	--% Mass --	t year ⁻¹		--% Mass --	t year ⁻¹		--% Mass --	t year ⁻¹		--% Mass --	t year ⁻¹		--% Mass --	t year ⁻¹	
Organic Matter	27.67	6.73	1.22	9.14	8.12	0.17	27.81	9.47	1.13	30.62	2.51	2.38	24.46	2.73	0.94
Paper/Cardboard	4.95	0.45	0.2	3.1	0.65	0.05	5.44	0.58	0.21	9.01	3.65	0.74	8.68	7.42	0.35
Plastic Film	18.04	15.84	0.49	47.65	16.52	0.65	29.02	6.09	1.11	27.32	8.61	2.23	10.81	3.39	0.41
Rigid Plastic	6.96	3.87	0.34	4.23	3.99	0.08	2.4	0.84	0.09	4.82	1.29	0.39	2.84	0.97	0.11
Metal	5.27	1.89	0.19	5.3	6.08	0.09	8.45	2.65	0.32	2.27	0.46	0.17	35.29	4.82	1.35
Glass	9.27	2.4	0.4	0	0	0	3.06	3.15	0.11	0.54	0.56	0.04	0	0	0
Pet	5.8	3.85	0.29	7.92	3.35	0.11	3.15	1.62	0.12	4.22	1.23	0.34	9.91	4.86	0.38
Long Life	1.25	0.79	0.04	6.19	3.4	0.09	2.66	2.56	0.09	1.29	1.41	0.09	2.27	2.6	0.09
Fabric/Leather	10.21	4.12	0.36	8.77	8.12	0.16	9.15	2.94	0.37	0.16	0.28	0.01	0	0	0
Others	10.58	12.4	0.52	7.7	3.47	0.1	8.87	4.55	0.37	19.76	9.91	1.46	5.73	4.17	0.23
Total	100	-	4.04	100	-	1.48	100	-	3.91	100	-	7.85	100	-	3.86

Source: The authors (2026).



Furthermore, the results of this study highlight a significant difference in solid waste fractions among the analyzed locations (Figure 2). Community dynamics are an important factor in waste generation, particularly for organic and plastic fractions. This variation in waste generation among communities may be related to population size, household income, family structure, pet ownership, and other factors (Li et al. 2021). High waste generation is a common reality in rural communities (Vinti & Vaccari 2022; Guimarães et al. 2024), especially due to extensive food production and the widespread use of plastic packaging (Li et al. 2021). However, this situation creates a viable opportunity for composting, transforming the generated waste into organic fertilizers useful for soil fertilization (Fidelis-Medeiros et al. 2020). On the other hand, the smaller amount of the fractions analyzed in Mirari suggests that the community may be more aware of the generation of this waste, corroborating the study by Nguyen et al. (2020), where increased awareness reduces waste generation.



*Letras em minúsculas diferentes indicam diferenças significativas entre os grupos pelo teste Tukey (5%).

Figure 2. Boxplot for the generation of organic material (a), paper/cardboard (b), plastic film (c), rigid plastic (d), metal (e), glass (f), PET (g), long-life packaging (h), and fabric (i) in the communities of Flexal (P1), Mirari (P2), Ilha do Tambaqui (P3), Paraisinho (P4), and Paraiso Grande (P5). Source: The authors (2026).

The final matrix of indicators for sustainable solid waste management is described in Table 4. Thus, the results showed that the stages in all communities were similar with regard to the management indicators.

Table 4. Indicators for sustainable solid waste management in the rural communities of Paraiso Grande, Paraisinho, Flexal, Mirari, and Ilha do Tambaqui

Indicators	Paráiso G.	Paráísinho	Flechal	Mirari	Island
Organizational Structure	EA (0)	EA (0)	EA (0)	EA (0)	EA (0)
Information Access Platform	ED (-1)	ED (-1)	ED (-1)	ED (-1)	ED (-1)
Public Participation in the Decision-Making Process	EC (-2)	EC (-2)	EC (-2)	EC (-2)	EC (-2)
Government support	EA (0)	EA (0)	EA (0)	EA (0)	EA (0)
Regular waste collection services	EC (-2)	EC (-2)	EC (-2)	EC (-2)	EC (-2)
Provision of services under RS	EC (-2)	EC (-2)	EC (-2)	EC (-2)	EC (-2)
Infrastructure (facilities and equipment)	EC (-2)	EC (-2)	EC (-2)	EC (-2)	EC (-2)
Prevention projects	ED (-1)	ED (-1)	ED (-1)	ED (-1)	ED (-1)

Source: The authors (2026).



The first indicator assesses the existence of the Municipal Plan for Integrated Solid Waste Management (PMGIRS), as well as the presence of an administrative structure responsible for urban cleaning services and the collection of household solid waste. All five communities received an EA (0) rating, reflecting the municipality of Humaitá's formal compliance with Federal Law No. 12,305/2010 (Brazil 2010), which establishes the National Solid Waste Policy and mandates the PMGIRS. In addition, regular collection services are available in urban areas and in some rural localities with road access.

However, it is essential to highlight that the homogeneity of results among the communities does not necessarily stem from equivalent conditions of operational performance, but rather from the normative and administrative centralization of management at the municipal level. Since all communities are subject to the same institutional framework, the same budgetary guidelines, and the same structural limitations, it is expected that indicators of an institutional nature will exhibit low spatial variability. This pattern is consistent with the literature, which indicates that the provision of public services and formal management instruments tend to reflect the administrative capacity of the municipal entity as a whole, rather than intra-municipal specificities (Fratta et al. 2019).

However, when analyzing the territorial effectiveness of management, a dissociation is observed between regulatory compliance and actual service coverage. Rural communities located in floodplain areas are not effectively served by the municipal solid waste management system. This finding corroborates the results of Oliveira et al. (2022a), who demonstrated that approximately 31% of Humaitá's population resides in rural areas, where practices such as burying or burning waste predominate, revealing a structural service deficit.

The second indicator, regarding the population's access to information on solid waste management, received an ED (-1) rating in all communities. The absence of systematized information, active transparency, and permanent communication strategies—in both physical and digital media—highlights weaknesses in information governance. The unavailability of public data compromises not only social control but also the development of a culture of shared responsibility in waste management.

In the third indicator, which assesses public participation in the decision-making process, the communities were classified as being in a critical state (EC -2), due to the lack of formal channels for social participation in the planning and monitoring of solid waste management actions, in both urban and rural contexts. This result demonstrates the limitations of the management model adopted, which remains predominantly top-down, with limited incorporation of participatory governance mechanisms.

The fourth indicator, regarding government support, placed the communities at the attention (EA) stage (0). Although a formal administrative structure exists, there is no specific planning tailored to the logistical peculiarities of areas accessible by river, which compromises the universalization of the service. The scientific literature emphasizes that sustainable solid waste management depends on the coordination of technical planning, continuous investments, adequate infrastructure, human resource training, and permanent environmental education programs (Fratta et al. 2019), elements that are still in their infancy in the analyzed context.

The fifth and sixth indicators, regarding the provision of regular collection services and the environmentally sound final disposal of solid waste, classified all communities as being in a critical state (EC -2). The lack of collection, transportation, and appropriate disposal results in the adoption of individual solutions, particularly the burning of waste on properties, a practice that intensifies environmental and health risks and reinforces the externalization of impacts onto the natural environment.

The seventh indicator, associated with infrastructure and equipment, also classified the communities as being in a critical state (EC -2). The absence of appropriate facilities, specific equipment, and logistics adapted to the rural-fluvial context highlights the structural limitations of the municipal integrated solid waste management system, particularly regarding the territorial inclusion of the most isolated communities.

Finally, the eighth indicator, regarding prevention projects, was classified as ED (-1). It was observed that the actions promoted by the Municipal Environment Secretariat occur sporadically, concentrated during festive periods—such as Carnival, religious festivals, agricultural exhibitions, and cultural festivals—without continuity or long-term strategic planning. Furthermore, it was found that there are no structured, permanent environmental education programs targeting the rural population. Additionally, Oliveira et al. (2022b) emphasize that ongoing guidance and awareness programs are essential for promoting behavioral changes, encouraging source separation, and increasing the efficiency of the solid waste management system.

Overall, the results show that the similarity in indices among communities reflects a structural pattern of municipal management, characterized by formal regulatory compliance but with operational limitations and low



territorial reach, especially in hard-to-reach rural areas. This finding reinforces the need for differentiated public policies that are territorially adapted and logistically compatible with the riverine reality, in order to promote greater equity in service delivery. However, this study has methodological limitations that must be considered when interpreting the findings. Although the communities' stages were found to be similar with respect to the analyzed indicators, the absence of systematized historical data prevented a more robust longitudinal analysis, limiting our understanding of the temporal evolution of municipal management. Furthermore, the sample limited to five communities reduces the potential for generalizing the results to other rural contexts with distinct socioeconomic, cultural, and environmental characteristics. It is therefore recommended that future research expand the sample base, incorporate historical data series, and adopt participatory approaches that promote greater community involvement in the collection, validation, and interpretation of information. Such strategies could increase the reliability of the results, deepen intermunicipal and cross- e comparative analyses, and support the formulation of more consistent and context-specific practical recommendations for local solid waste management.

Conclusion

The analysis of solid waste management in rural areas of the Amazon region highlights the need for structural and operational improvements to minimize environmental impacts and promote better living conditions for local populations. As observed, the method most commonly used by community members is still the burning of inorganic solid waste in open pits, a practice that can generate environmental impacts and health risks. The solid waste fractions showed significant differences among the analyzed sites, with a predominance of organic material, followed by plastic film. The indicator matrix for sustainable solid waste management revealed that the communities' stages were similar in relation to management indicators, indicating common challenges and opportunities for integrated actions.

Given this scenario, the implementation of community composting programs is recommended, considering the high organic fraction identified, as well as the establishment of separate collection systems for recyclable waste, especially plastics. Furthermore, ongoing environmental education initiatives are essential to raise public awareness regarding waste reduction, reuse, and proper disposal. The methodology employed in this study can be applied in other municipalities to assess the adequacy and scope of the indicators in different territorial contexts. The information generated may support the formulation of an integrated solid waste management plan, effectively contributing to the reduction of environmental impacts and the improvement of quality of life in rural communities in the Western Amazon.

Acknowledgments

The authors would like to thank the Amazonas Research Support Foundation (FAPEAM) for funding this research (grant no. 01.02.016301.03254/2021-56).

References

- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JDM, Sparovek G 2013. Köppen's climate classification map for Brazil. *Meteorol Z* 22:711–728.
- Barros RTV, Silveira AVF 2019. Use of sustainability indicators to evaluate urban solid waste management in the Belo Horizonte Metropolitan Region. *Eng Sanit Ambient* 24:411–423.
- Bernardes C, Günther WMR 2014. Generation of domestic solid waste in rural areas: case study of remote communities in the Brazilian Amazon. *Hum Ecol* 42:617–623.
- Bezerra GAAO, Wankler FL 2023. Solid waste disposal in indigenous villages in Roraima: alternatives and solutions for rural sanitation. *Rev Bras Educ Ambient* 18:87–96.
- Brazil 2010. Law No. 12,305, of August 2, 2010. Executive Branch, Brasília.



- Caiado LC, Campos LC, da Fonseca-Zang W, Zang J, Bleischwitz R 2021. Water, waste, energy, and food nexus in Brazil: Identifying a resource interlinkage research agenda through a systematic review. *Renew Sustain Energy Rev* 138:110554.
- Carneiro GO, Nascimento JO, Santos LMF, Pragana RB 2024. Assessment of the quality of organic compost produced through home composting. *Rev GEAMA* 10:20–27.
- Castro LRC, Almeida FFS, Cavalcante AMS, Guimarães IRB, Silva VM, Lisboa FAM, Nascimento TV 2020. Health overview of riverside populations in the Brazilian Amazon and applicable social technologies. *Res Soc Dev* 9:e5891210898–e5891210898.
- Castro MAO, Silva NM, Marchand GAEL 2015. Developing indicators for the sustainable management of solid waste in the municipalities of Iranduba, Manacapuru, and Novo Airão, Amazonas, Brazil. *Eng Sanit Ambient* 20:415–426.
- Cempre 2018. *Municipal waste: integrated management manual*. 4th ed., São Paulo, 316 p.
- Cervantes DET, Martínez AL, Hernandez C, Cortázar ALG 2018. Using indicators as a tool to evaluate municipal solid waste management: A critical review. *Waste Manag* 80:51–63.
- Devendran AA, Mainali B, Khatiwada D, Golzar F, Mahapatra K, Toigo CH 2023. Optimization of municipal waste streams in achieving urban circularity in the city of Curitiba, Brazil. *Sustainability* 15:3252.
- Fidelis-Medeiros FH, Lunardi VO, Lunardi DG 2020. Proposal for the proper management of household solid waste in rural communities using spatial analysis. *Rev Bras Geogr Fís* 13:527–543.
- Fratta KDSA, Toneli JTCL, Antonio GC 2019. Diagnosis of the management of solid urban waste in the municipalities of the ABC Paulista region of Brazil through the application of sustainability indicators. *Waste Manag* 85:11–17.
- Guimarães GA, Santos CA, Mitouso DTS, Rosário MR, Garcia ADC, Kuwano RT, Alves RC, Oliveira BOS 2023. Assessment of final disposal sites for urban solid waste in Itacoatiara, Amazonas. *Fronteiras J Soc Technol Environ Sci* 12:49–62.
- Guimarães GA, Santos CA, Mitouso DTS, Rosário MR, Pantoja KLG, Batista MM, Alves RC 2024. Characteristics and management of municipal solid waste in rural districts in the interior of Amazonas. *Rev Bras Geogr Fís* 17:1658–1671.
- IBGE 2023. Overview of the municipality of Humaitá. Brazilian Institute of Geography and Statistics, Brasília.
- Jucá JFT, Barbosa KRM, Sobral MC 2020. Sustainability indicators for municipal solid waste management: A case study of the Recife Metropolitan Region, Brazil. *Waste Manag Res* 38:1450–1454.
- Li Y, Wang L, Liu G, Cheng S 2021. Rural household food waste characteristics and driving factors in China. *Resour Conserv Recycl* 164:105209.
- Lima PM, Morais MF, Constantino MA, Paulo PL, Magalhães Filho FJC 2021. Environmental assessment of waste handling in rural Brazil: Improvements toward a circular economy. *Cleaner Environ Syst* 2:100013.
- Lima PM, Paulo PL 2018. Solid-waste management in rural Brazil: A case study in Quilombola communities. *J Mater Cycles Waste Manag* 20:1583–1593.
- Morais L, Nascimento V, Simões S, Ometto J 2021. Estimation of regional transport distances for municipal solid waste disposal: A case study of São Paulo State, Brazil. *Energies* 14:3964.



- Nguyen KLP, Chuang YH, Chen HW, Chang CC 2020. Impacts of socioeconomic changes on municipal solid waste characteristics in Taiwan. *Resour Conserv Recycl* 161:104931.
- Olay-Romero E, Turcott-Cervantes DE, Hernández-Berriel MC, Cortázar ALG, Cuartas-Hernández M, Rosa-Gómez I 2020. Technical indicators to improve municipal solid waste management in developing countries: A case in Mexico. *Waste Manag* 107:201–210.
- Oliveira BOS, Medeiros GA 2020. Municipal solid waste management in the Amazon: Environmental, social, and economic problems, gaps, and challenges. *WIT Trans Ecol Environ* 245:9–20.
- Oliveira BOS, Medeiros GA, Mancini SD, Paes MX, Gianelli BF 2022a. Eco-efficiency transition applied to municipal solid waste management in the Amazon. *J Clean Prod* 373:133807.
- Oliveira BOS, Tucci CAF, Neves Júnior AF, Santos AA 2016. Assessment of soils and waters in the areas of influence of municipal solid waste disposal in Humaitá, Amazonas. *Eng Sanit Ambient* 21:593–601.
- Oliveira MCVD, Klafke R, Chaerki SF 2022b. The challenge of municipal solid waste management in Brazil. *Econ Soc Territ* 22:177–206.
- Palansooriya KN, Dissanayake PD, Igalavithana AD, Tang R, Cai Y, Chang SX 2023. Converting food waste into soil amendments for improving soil sustainability and crop productivity: A review. *Sci Total Environ* 881:163311.
- Pereira SS, Curi RC, Curi WF 2018. Use of indicators in municipal solid waste management: A methodological proposal for construction and analysis for municipalities and regions. *Eng Sanit Ambient* 23:471–483.
- Pereira TS, Fernandino G 2019. Evaluation of solid waste management sustainability in a coastal municipality in northeastern Brazil. *Ocean Coast Manag* 179:104839.
- R Core Team 2024. *The R Project for Statistical Computing*. R Foundation for Statistical Computing, Vienna.
- Raihan A 2023. The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. *Energy Nexus* 9:100180.
- Santiago LS, Dias SMF 2012. Matrix of sustainability indicators for urban solid waste management. *Eng Sanit Ambient* 17:203–212.
- Silva GJA, Pessali HF 2018. Proposed indicators for cooperation in shared solid waste management. *Rev Cienc Adm* 20:63–83.
- Silva L, Prietto PDM, Korf EP 2019. Sustainability indicators for urban solid waste management in large and medium-sized cities worldwide. *J Clean Prod* 237:117802.
- Silva RMG, Nóbrega CC, Sá ACND, Silva DLV, Firmino LDQ 2023. Sustainability indicators for analyzing the management of waste electrical and electronic equipment. *Eng Sanit Ambient* 28:e20220220.
- SNIS 2022. 2020 Solid Waste Management Assessment. National Sanitation Information System, Brasília.
- Souza CCF, Melo BR, Santos MAS, Rebello FK, Martins CM, Beltrão NES 2019. Assessment of sustainability in solid waste management in the municipality of Marituba, Belém Metropolitan Region, state of Pará. *Rev Metrop Sustentab* 9:115–136.
- Vinti G, Vaccari M 2022. Solid waste management in rural communities of developing countries: An overview of challenges and opportunities. *Clean Technol* 4:1138–1151