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Impact of collection from indigenous lands on the municipal solid waste management system: A case study in the Amazon

Impacto da coleta em terras indígenas no sistema de gestão dos resíduos sólidos municipais: Um estudo de caso na Amazônia

Impacto de la recolección en tierras indígenas en el sistema de gestión de residuos sólidos municipales: Un estudio de caso en la Amazonía

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Beatriz Hanada Menichelli
ORCID: https://orcid.org/0009-0004-9568-5926
Universidade Estadual Paulista, Brazil
E-mail: beatriz.hanada@unesp.br
Benone Otávio Souza de Oliveira
ORCID: https://orcid.org/0000-0002-5404-0409
Universidade Federal do Amazonas, Brazil
E-mail: benone@ufam.edu.br
Gerson Araujo de Medeiros
ORCID: https://orcid.org/0000-0002-9122-3909
Universidade Estadual Paulista, Brazil
E-mail: gerson.medeiros@unesp.br

Abstract
In the Amazon, solid waste collection is generally restricted to urban areas, excluding indigenous lands and rural areas. The objective of this research was to analyse the impact of collecting waste generated from indigenous lands on the municipal solid waste (MSW) management system, through life cycle assessment (LCA). A case study in the Humaitá city, state of Amazonas, Brazil, was based on life cycle inventory data, obtained from literature and field surveys, such as the waste gravimetry. The LCA followed the model proposed by ISO 14040 and 14044 and estimated greenhouse gas (GHG) emissions for three MSW management scenarios. The first, called Base Scenario (SB), corresponded to that practiced in Humaitá: collection of MSW from the urban area, logistic, and disposal in landfill. The second scenario (S1) corresponded to SB and the collection of waste generated on indigenous lands in that municipality. The third scenario (S2) corresponded to S1, excluding organic waste, which would be destined for composting on indigenous lands. The base scenario totalled an emission of 1,539 t CO_2eq.year^{-1}. Collecting solid waste from indigenous lands would increase these GHG emissions by 5.2% (S1) and 0.9% (S2) in relation to SB. The decentralized management of organic waste through composting associated with the separation and storage of dry waste would reduce the burning of waste in indigenous areas, their environmental vulnerability and promote the inclusion of these peoples.
Keywords: Climate change; Greenhouse gases; Environmental impact; Logistics.

Resumo
Na Amazônia a coleta de resíduos sólidos geralmente se restringe ao meio urbano, excluindo-se terras indígenas e área rural. O objetivo do presente trabalho foi analisar o impacto da coleta de resíduos gerados em terras indígenas no sistema de gestão de resíduos sólidos municipais (RSM), por meio da avaliação do ciclo de vida (ACV). Um estudo de caso no município de Humaitá, estado do Amazonas, se baseou em dados do inventário do ciclo de vida, obtidos na literatura e levantamentos de campo, como a gravimetria dos resíduos. A ACV seguiu o modelo proposto pela ISO 14040 e 14044 e estimou as emissões de gases de efeito estufa (GEE) para três cenários de gestão dos RSM. O primeiro, chamado de Cenário base (SB), correspondeu aquele praticado em Humaitá: coleta dos RSM da área urbana, logística e sua disposição em aterro. O segundo cenário (S1) correspondeu ao SB e a coleta dos resíduos gerados nas terras indígenas desse município. O terceiro cenário (S2) correspondeu ao S1, excluindo os resíduos orgânicos, que seriam destinados à compostagem nas terras indígenas. O cenário base atingiu uma emissão de 1.539 t CO_2eq.ano^{-1}. A logística da coleta dos resíduos sólidos das terras indígenas elevaria essas emissões de GEE em 5,2% (S1) e 0,9% (S2) em relação ao SB. A gestão descentralizada dos resíduos orgânicos por meio da compostagem associada à separação e armazenamento dos resíduos secos, reduziria a queima de resíduos nas áreas indígenas, sua vulnerabilidade ambiental e promovendo a inclusão desses povos.
Palavras-chave: Mudanças climáticas; Gases de efeito estufa; Impacto ambiental; Logística.

Resumen
En la Amazonía, la recolección de residuos sólidos generalmente está restringida a las áreas urbanas, excluyendo las tierras indígenas y las áreas rurales. El objetivo de esta investigación fue analizar el impacto de la recolección de residuos generados en tierras indígenas en el sistema de gestión de residuos sólidos municipales (RSU), a través del análisis del ciclo de vida (ACV). Un estudio de caso en la ciudad de Humaitá, estado de Amazonas, Brasil, se basó en datos de inventario del ciclo de vida, obtenidos de la literatura y estudios de campo, como la gravimetría de residuos. El ACV siguió el modelo propuesto por las normas ISO 14040 y 14044 y estimó las emisiones de gases de efecto invernadero (GEI) para tres escenarios de gestión de RSU. El primero, denominado Escenario Base (SB), correspondió al practicado en Humaitá: recolección de RSU del área urbana, logística y disposición en relleno sanitario. El segundo escenario (S1) correspondió a la SB y la recolección de residuos generados en tierras indígenas de ese municipio. El tercer escenario (S2) correspondió al S1, excluyendo los residuos orgánicos, que serían destinados a compostaje en tierras indígenas. El escenario base totalizó una emisión de 1.539 t CO_2eq.año^{-1}. La recolección de residuos sólidos en tierras indígenas aumentaría estas emisiones de GEI en un 5,2% (S1) y un 0,9% (S2) con relación a la SB. El manejo descentralizado de los residuos orgánicos mediante compostaje asociado a la separación y almacenamiento de residuos secos reduciría la quema de residuos en zonas indígenas, su vulnerabilidad ambiental y promovería la inclusión de estos pueblos.
Palabras clave: Cambio climático; Gases de invernadero; Impacto ambiental; Logística.

1. Introduction

The growth in the global generation of municipal solid waste (MSW) has increased the risks to human health, through pollution of soil, air, surface, and underground waters (Paes et al., 2014). This situation creates challenges for contemporary society, leading several governments to prioritize the hierarchy of MSW, highlighting the reduction of generation, treatment of waste and, as a last option, final disposal in landfills, as observed in Brazil (Paes et al., 2020b) and Angola (Cristóvão et al., 2022).

In Brazil, only 2.2% of MSW is recovered in sorting structures, with 60% disposed of in landfills and 25% in open dumps and controlled landfills, despite the priority given to reduction and recovery (Mancini et al., 2021). In this panorama, the Brazilian Amazon presents the most unfavorable situation, as more than 80% of the municipalities in this region have MSW in open dumps and controlled landfills (Oliveira & Medeiros, 2019).

Several aspects justify this reality in the Amazon, highlighting the territorial and demographic characteristics, such as the low population density, high territorial extension, the precarious logistical structure, and the incipient industrial park, in addition to the rainfall index, the highest in Brazil (higher than 2,500 mm per year) (Mancini et al., 2021). Such conditions limit the implementation of integrated MSW management alternatives and modern approaches such as the circular economy (Oliveira et al., 2021, Mancini et al., 2021).

The territorial isolation of the Amazon, both in Brazil and in other South American countries, is also reflected in the scarce literature on MSW management in this hotspot region of the planet, according to a survey carried out by Oliveira & Medeiros (2020). Through this survey, a significant disposal of solid waste was observed in open dumps and controlled landfills in the Amazon of Brazil, Bolivia, Colombia, Guyana, Peru, and Venezuela, associated with recycling rates that varied from 0.2 to 3.9% (Oliveira & Medeiros, 2020).

Another relevant aspect in the discussion about MSW management in the Amazon refers to the significant area of indigenous lands. In Brazil, around 13.8% of its territory corresponds to indigenous lands (1.18 million km^2) and, of this total, around 98% is concentrated in the Amazon (1.15 million km^2) (FUNAI, 2021).

Indigenous communities on the American continent, including those in the Amazon, have precarious access to various social and basic sanitation services, such as solid waste collection. Ancestral practices of pre-Columbian indigenous peoples consisted of burying waste generated in the soil, promoting the anthropogenic enrichment of its fertility, and giving rise to Black Earth, lands with a high concentration of phosphorus and organic matter (Orozco-Ortiz et al., 2021). However, the expansion of human occupation in the Amazon indigenous lands through mining (Salomão et al., 2023), agriculture and livestock (Riquetti et al., 2023), logging (Lapola et al., 2023), tourism (Peredo & Wurzelmann, 2015, Maldonado-Erazo et al., 2023) and urbanization

(Ferreira et al., 2021, Araújo et al., 2023) have influenced human vulnerability and environmental systems, through the increase in the generation of dry waste such as plastic, paper, metal and glass (Jaramillo et al., 2023, Vélez et al., 2019), batteries and chemical waste (Sanches et al., 2021), and waste from health services (Aleixo & Braga, 2022).

The absence of waste collection in indigenous lands on the American continent has led to reports of the burning of plastic, paper and other waste in Guatemala (Cruz et al., 2023), Ecuador (Jaramillo et al., 2023, Peñafiel-Arcos et al., 2022, Vélez et al., 2019), Peru (Gascón, 2022), Colombia (Morales-Pérez et al., 2023), and Canada (Keske et al., 2018, Assuah & Sinclair, 2021, Wang et al., 2023), or its disposal in landfills in Canada (Oyegunle & Thompson, 2018, Assuah & Sinclair, 2021, Wang et al., 2023), Ecuador (Heredia et al., 2020) and Brazil (Aleixo & Braga, 2022) . These practices are observed in remote communities and increase the risks to the health of these people, through pollution of water, soil, and atmosphere, in addition to greenhouse gas (GHG) emissions (methane and carbon dioxide) (Salim et al., 2023, Fernández-Llamazares, 2020).

Therefore, decision-making and evaluation of solid waste management scenarios in indigenous lands emerge as challenges, especially in the Amazon, a region that concentrates the largest indigenous population on the planet, reaching around 355,000 individuals (Rorato et al., 2022). The complexity of the environmental, social, cultural, political, and economic aspects involved in analyzing the impacts of MSW management scenarios, in the context of indigenous lands in the Amazon, introduces the life cycle assessment (LCA) approach (Oliveira et al., 2022).

LCA is a tool for modelling and quantifying environmental impacts generated from products or processes, throughout their life cycle, from the cradle (extraction of raw materials) to the grave (final disposal) (Laurent et al., 2014). In this methodological approach, a compilation of the inputs and outputs of matter and energy underlies the assessment of the potential environmental impacts of a product system, throughout its life cycle (Paes et al., 2020a). Research involving LCA has applications in evaluating scenarios for different sectors of society, such as agriculture (Costa et al., 2018), education (Dutra et al., 2019), laboratory processes (Melo et al., 2023) and in the MSW management (Paes et al., 2020a, Oliveira et al., 2022).

In Brazil, LCA studies related to solid waste management have been disseminated in different regions, predominantly the Southeast (Paes et al., 2020a, Paes et al., 2020b) and South (Mersoni & Reichert, 2017). However, there is a gap in research carried out in the Amazon, highlighting Oliveira et al. (2022).

In the state of Mato Grosso do Sul, Brazil, in isolated rural communities known as Quilombos, live the descendants of fugitive black slaves, known as Quilombolas. In these communities there is no access to solid waste collection (Lima & Paulo, 2018), and waste the management is limited to burning the household waste, as practiced by the indigenous people of the American continent (Gascón, 2022, Jaramillo et al., 2023, Wang et al., 2023). However, this practice leads to risks to human health and the ecosystem, highlighting the impacts related to human toxicity and ecotoxicity of fresh water, as investigated by Lima et al. (2021) using life cycle assessment (LCA).

Therefore, the objective of this research was to analyse the impact of collecting waste generated on indigenous lands on the municipal solid waste management system, through life cycle assessment (LCA). A case study was developed in the municipality of Humaitá, in the state of Amazonas, Brazil, when greenhouse gas (GHG) emissions were evaluated for different waste collection scenarios on indigenous lands.

2. Methodology

2.1 Social, environmental, and economic characterization of Humaitá

The humid equatorial climate of the state of Amazonas has an average annual temperature ranging from 26 to 28 ºC and precipitation above 2,000 mm.year^{-1} (Dalagnol et al., 2017). The municipality of Humaitá (Figure 1), at coordinates 07° 30' 22''S and 63° 01' 15'' W and 90 m, is 700 km away from the metropolitan region of Manaus (Brasil, 2021).

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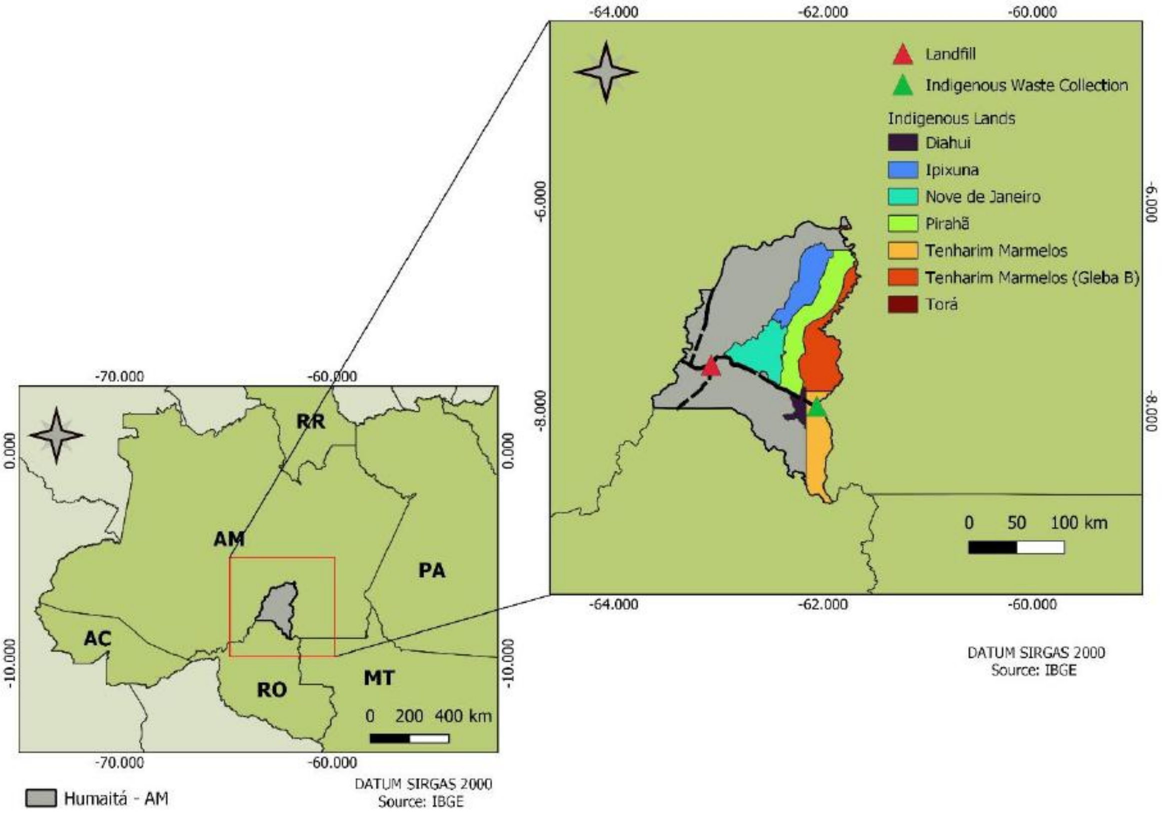
Figure 1 - Distribution of indigenous communities, landfill and MSW collection site on indigenous lands, Municipality of Humaitá, state of Amazonas (AM), Brazil.



Source: Authors, based in IBGE (2018).

With a territory of 33,144 km² and an estimated population of 56,144 inhabitants, in 2020, its population density reached 1.70 inhabitants.km^{-2} (IBGE, 2020). However, this demographic density presents significant differences when comparing urban, rural, and indigenous populations, as around 38,700 inhabitants lived in urban areas (4.5 inhabitants.km^{-2}) and 17,400 inhabitants in rural areas (0.98 inhabitants.km^{-2}) (Oliveira et al., 2022).

Indigenous lands occupy around 46% of the municipality's area and its population reached 2,231 inhabitants (0.14 inhab.km^{-2}) in 2014, according to data from the Special Secretariat for Indigenous Health made available by the Instituto Socioambiental (ISA) (ISA, 2020). These forest lands have specific legal and environmental restrictions (Oliveira & Medeiros, 2020).

2.2 Proposed scenarios for the management of Humaitá's MSW

The scenarios proposed for the management of MSW in Humaitá were based on the sorting of MSW, composting of organic waste and landfilling of the remainder, following the recommendations of experts for the Southwest Amazon region, according to research carried out by Oliveira et al. (2021). The following scenarios were evaluated, with the inclusion of waste collection on indigenous lands:

2.2.1 Base scenario (SB)

In this scenario, the MSW management system practiced in Humaitá was modeled: collection and transportation of waste generated only in the urban area, without prior sorting, and disposal in a landfill, replacing the controlled landfill, a practice currently adopted in the municipality. MSW collection reached 5,412 t.year^{-1} (dry and organic waste), using two 5 m³ compactor trucks, with a frequency of 6 days per week in residential neighborhoods, and every day in in the commercial area of the city (Oliveira et al., 2022).

2.2.2 Scenario 1 (S1)

This scenario corresponded to the SB with the collection of waste generated on indigenous lands, and subsequent disposal in the municipality's landfill. In Humaitá, indigenous lands are inhabited by the following ethnic groups: Diahui (115 indigenous people), Ipixuna (64 indigenous people), Nove de Janeiro (206 indigenous people), Pirahã (592 indigenous people), Tratarins Marmelos (535 indigenous people), Suasrins (393 indigenous people) and Torah (326 indigenous people), based on data from the National Foundation of Indigenous Peoples (FUNAI) (FUNAI, 2021).

The generation of household solid waste on indigenous lands is influenced by economic issues, urbanization, and community isolation (Gascón, 2022). Records of household waste generation in Amazonian indigenous communities can vary from 0.20 kg.inhabitant^{-1} (Peñafiel-Arcos et al., 2022) to 0.34 kg.inhabitant^{-1} (Jaramillo et al., 2023). In the present work, we consider a daily generation of 0.26 kg.inhabitant^{-1}, based on research carried out with indigenous communities in the Ecuadorian Amazon (Vélez et al., 2019), as the isolation conditions are closer to those observed in the indigenous communities of Humaitá. According to the survey by these authors, around 75% of the waste generated was organic and 18% considered reusable (metals, plastic, and cardboard). This gravimetry differs from that observed in indigenous peoples in northern Canada, as organic waste reaches 38% and dry recyclable waste accounts for around 36% of the total (Wang et al., 2023). This difference demonstrates the importance of considering the local specificities of indigenous peoples, such as the context and needs of the community, the volume and type of generated waste (Salim et al., 2023).

The Indigenous Health House, located in the territory of the Tratarim ethnic group, was selected to collect waste generated in indigenous lands (Figure 1), 130 km from the urban area of Humaitá, as this health center serves 70% of the indigenous population of this municipality (Oliveira et al., 2022). The low demographic density and spatial dispersion of indigenous peoples, in addition to the use of boats to cross the Madeira River, make waste logistics difficult. Therefore, we defined a weekly collection of waste generated on indigenous lands.

2.2.3 Scenario 2 (S2)

In scenario 2, S1 is repeated, however, only dry solid waste from indigenous lands would be sent to landfill, while the organic fraction would be sent to compost on the indigenous land itself.

2.3 Life Cycle Assessment (LCA)

The environmental performances of indigenous waste management were assessed based on an attributional LCA with a cradle to grave approach, following the model proposed by ISO 14040 (ISO, 2014a) and 14044 (ISO, 2014b). The LCA consisted of the following steps: definition of objective and scope, inventory analysis, impact assessment and interpretation of results. The simulation of the proposed scenarios was carried out using the SimaPro software, version 9.2.

The objective of LCA was to evaluate greenhouse gas emissions (CO_2eq), caused by the proposed management scenarios for Humaitá's MSW. The scope included the following management stages of municipal solid waste management: collection, transportation, and final disposal in a sanitary landfill.

The system's function follows the proposal of managing the activities necessary for the collection, transportation, and final disposal of 5,412 t year^{-1} of MSW generated in Humaitá, state of Amazonas, Brazil.

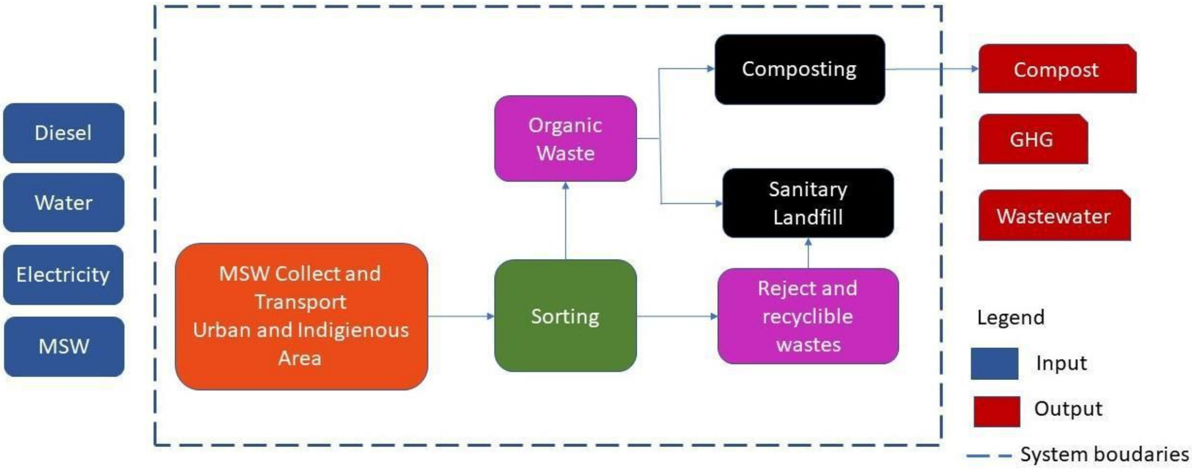
System boundary corresponded to the cradle-to-grave model, including the stages of collection, transportation, and final disposal, associated with leachate generation, fuel consumption and atmospheric emissions (Figure 2).

Life Cycle Inventory (LCI) based on the Ecoinvent 3 database selected the closest option to a Brazilian landfill, including the inputs and outputs of matter and energy related to its construction and operation (excavation, transport and compaction of waste using tractors). Gravimetric surveys of solid waste generated in the urban area, and secondary data were obtained from a research partnership between the São Paulo State University (Unesp) and the Universidade Federal do Amazonas (UFAM). MSW gravimetric composition was surveyed at the municipal landfill and published by Oliveira et al. (2022). According to these authors, Humaitá generated 14.83 $t.day^{-1}$ of MSW (5,412 $t.year^{-1}$) or 0.4 $kg.day^{-1}$ per capita. Organic matter predominated (44%), followed by plastic (16%) and cardboard (10%). This gravimetry corroborates results compiled from other Amazon regions on the American continent, such as Bolivia, Ecuador, Peru, and Suriname (Oliveira et al., 2021).

Information about the transport and collection of MSW, the route and distances covered by the trucks were based on the survey by Souza et al. (2018). Waste collection only covered the urban area of the city, and included four routes covered by two compactor trucks, the first with a capacity of 5.5 t and the second of 4.5 t. Both traveled, on average, 50 km per day and were supplied weekly with 260 L of diesel oil, reaching an average yield of 1.34 $km.L^{-1}$, or a consumption of 46.3 t per year.

The estimation of the impacts of municipal solid waste logistics followed the methodology described by Oliveira et al. (2022) with secondary data from the Motor Vehicle Air Pollution Control Program (Proconve). In the LCA, we estimated the environmental impact category greenhouse gas (GHG) emissions, expressed in CO_2eq, according to WRI (2015). Greenhouse gas emissions were estimated by converting the mass units of each gas emitted using the Global Warming Potential (GWP) metric, defined by the Greenhouse Gases (GHG) Protocol method recommended by the Intergovernmental Panel on Climate Change (IPCC) (WRI, 2015, Houghton et al., 2001).

Figure 2 - Schematic representation of the product system comprising the MSW management system for Humaitá, Amazonas state, Brazil.



Source: Authors.

3. Results and Discussion

3.1 LCI and Impacts of the Waste Management Scenarios

In Table 1 you can see the inventory of materials and energy used in the LCA of the evaluated scenarios, including data from the collection and transport of MSW.

Waste generated annually on indigenous lands reached around 181 t, based on estimates by Vélez et al. (2019), and the

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dry fraction corresponded to 32.7 t (18.1% of the total). Thus, collection on indigenous lands would represent an increase in the amount of MSW disposed of at the Humaitá landfill of 3.3% (S1) and 0.6% (S2) in relation to the base scenario (SB).

The SB scenario reached a GHG emission of 1,539 t CO_2eq.year^{-1}. The introduction of waste collection in indigenous areas would increase greenhouse gas emissions to 1,620 t CO_2eq.year^{-1} in S1, or an increase of 5.2% in relation to SB, due to the addition of 14,400 km in RSM logistics. Despite the same logistics, the impact of S2 was smaller and reached 1,553 t CO_2eq.year^{-1}, representing an increase of 0.9% in relation to SB.

Around 94% of GHG emissions in the SB scenario refer to the landfill disposal, while in scenarios S1 and S2 these values reached 93% and 94% respectively. Research evaluating MSW management scenarios in the cities of Sorocaba (Paes et al., 2020a) and Humaitá (Oliveira et al., 2022), through LCA, also indicated that landfill disposal causes the greatest environmental impact on the Municipal solid waste management system.

Waste collection in indigenous areas increased fuel consumption by 11.7% and the amount of waste disposed of at the Humaitá landfill by 3.9% and 0.9% in scenarios S1 and S2 respectively. Carbon dioxide emissions in the collection and transport stage were the most impacted with waste collection in indigenous areas reaching a growth of 30% and 4.2% in scenarios S1 and S2 respectively. This result demonstrated the reduction of the impact on GHG emissions when transporting only dry waste from indigenous lands and its subsequent disposal in the Humaitá landfill, as it reduced the truck load and, consequently, fuel consumption and GHG emissions.

In the landfill disposal stage, the magnitude of the increase in GHG emissions was lower, reaching 3.7% and 0.7% for S1 and S2 in relation to the SB scenario. This result is due, in part, to the hypothesis of a negligible increase in diesel consumption for lighting the landfill and compacting the MSW for scenarios S1 and S2. Leachate generation increased by 3.9% and 1.0% and methane emissions by 3.6% and 0.4% in scenarios S1 and S2 in relation to SB, respectively.

Alternatives for treating organic waste vary according to the environmental conditions where indigenous lands are located. In northern Canada, adverse climatic conditions, such as extremely low temperatures and prolonged winters, make biological processes and the decomposition of organic waste unfeasible (Keske et al., 2018). In this environment, biochar attracts greater interest as a soil fertilizer and for remediation purposes in contaminated areas (Keske et al., 2018).

In the Amazon, composting is a suitable solution for managing organic waste from isolated communities, such as indigenous communities (Jaramillo et al., 2023, Peñafiel-Arcos et al., 2022, Salim et al., 2023) or Quilombolas (Lima et al., 2021). This technique has considerable acceptance among indigenous communities in the Amazon to produce fertilizers and use in agriculture (Jaramillo et al., 2023).

Paes et al. (2020b) evaluated GHG emissions from MSW management scenarios in the city of Humaitá, state of Amazonas using the CO2ZW tool, which was specially developed to compare MSW management scenarios considering different treatment alternatives. According to these authors, a diversion from the landfill of 10% of wet waste to composting and 10% of dry waste to recycling would reduce GHG emissions in 10%. In the municipality of São Paulo, state of São Paulo, Brazil, diverting 10% of organic waste and 10% of recyclable waste from sanitary landfill would represent a 9% reduction in GHG emissions, and savings of US$66.7 million per year, considering alone operational costs (Paes et al., 2021).

Table 1 - Life Cycle Inventory of municipal solid waste management scenarios: base scenario (SB) without collection on indigenous lands; S1 scenario with the inclusion of collection on indigenous lands and transportation of all waste generated to the landfill; S2 scenario with the transport of only dry waste to the landfill (C2), in Humaitá, state of Amazonas, Brazil.

Stage	Materials/Emissions	Units	SB	S1	S2
Collection and Transport	Diesel Oil Consumption	t.year^{-1}	46.3	51.7	51.6
	MSW Transport	t.km.year^{-1}	270,100	301,734	278,193
	Carbon dioxide	t CO_2eq.year^{-1}	88.3	115.0	92.0
	Carbon monoxide	t CO_2eq.year^{-1}	1.8	1.8	1.8
Landfill disposal	Diesel Oil Consumption	t.year^{-1}	16.6*	16.6	16.6
	Electric power consumption	kWh.year^{-1}	7,200	7,200	7,200
	Waste disposal	t.year^{-1}	5,412	5,622	5,465
	Carbon dioxide	t CO_2eq.year^{-1}	774	804	781
	Methane	t CO_2eq.year^{-1}	675	699	677
	Leachate	t.year^{-1}	217	225	219

***** Total annual diesel consumption includes the use of 46.3 t for transportation and collection, 14.76 t for landfill operation activities and 1.84 t for lighting the landfill. (Oliveira et al., 2022). Source: Authors.

Lima et al. (2021) estimated the generation and composition of domestic solid waste in Quilombola communities. This generation reached an average of 0.63 kg.hab.day^{-1}, predominantly organic waste (67%), followed by plastic (11%), glass (10%), paper and metal (5% each). Management corresponds to open burning of 73% of waste, 24% sent to landfill and 2.4% buried, a reality close to that observed in indigenous communities. Based on the life cycle assessment, these authors estimated an emission of 415 kg CO_2.(t MSW)$^{-1}$ for this MSW management scenario. Of this total emissions, around 99% corresponds to the burning of waste, or approximately 410 kg CO_2.(t MSW)$^{-1}$. The introduction of home composting replacing the waste burning would reduce GHG emissions to 2.26 kg CO_2.(t MSW)$^{-1}$.

In the Amazon, the recycling structure is much more precarious compared to other more industrialized Brazilian regions, such as the Southeast and South, as there are only two recycling markets, in the capitals of Manaus and Belém, representing a barrier to the circular economy (Oliveira et al., 2022, Mancini et al., 2021). Therefore, the composting of organic waste in indigenous lands associated with the storage of dry waste, and subsequent sending to the Humaitá landfill, would contribute to reducing the emissions estimated for scenario S2 and the impact of waste collection in these areas.

Other alternatives for waste management in indigenous lands could be developed based on ancestral knowledge for prevention, reduction, and reuse, according to Siragusa and Arzyutov (2020). Experience in this direction has been reported in rural communities of the Zenú Indigenous Reserve, in the Colombian Amazon (Morales-Pérez et al., 2023).

4. Conclusion

Waste collection on indigenous lands caused an increase in greenhouse gas emissions from Humaitá's solid waste management system. However, the decentralized management of organic waste through the development of composting in these areas can be an alternative to reducing the volume of waste disposed of in landfills. The positive impacts of this management alternative are enhanced in indigenous lands due to the significant relative importance of organic waste. Thus, there would be a reduction in the volumes transported by the collection system and disposed of at the Humaitá landfill. Furthermore, they would reduce emissions from burning waste, a common practice in isolated communities without access to collection. Structures for storing dry waste for later collection and sending to landfill would improve the system's efficiency and optimize logistics. Therefore, the inclusion of waste collection from indigenous areas, despite the increase in GHG emissions, would reduce the vulnerability of these populations, according to literature reports.

This article emerges possibilities for research in solid waste management in indigenous communities in the Amazon. Research must address issues such as: evaluation of gravimetry and generation of solid waste in indigenous lands, development of alternatives for decentralized solid waste management appropriate to the environmental and cultural conditions of indigenous communities and based on ancestral knowledge; optimization of dry waste collection routes in indigenous lands and rural areas of the Amazon, linked to river and road transport and recycling chains.

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