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Assessment of the impact of greenhouse gas emissions in different municipal residual waste treatment scenarios: a case study in the municipality of Juiz de Fora (MG) — Brazil

Avaliação do impacto das emissões de gases de efeito estufa em diferentes cenários de tratamento de resíduos sólidos urbanos: estudo de caso no município de Juiz de Fora (MG) — Brasil

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ABSTRACT

Population growth leads to more municipal solid waste (MSW) production, increasing environmental and human health impacts. The National Solid Waste Policy, established by Law No. 12,305/2010, required municipalities to rethink waste management, prioritizing recycling and treatment over final disposal in landfills. This study aimed to assess the environmental impact of greenhouse gas (GHG) emissions from different MSW recovery scenarios in Juiz de Fora, Minas Gerais, using the "GHG Emissions Calculator for MSW Management in Brazil" tool, based on the Life Cycle Assessment methodology. Four scenarios were evaluated, taking into account MSW generation characteristics in the municipality for 2017 and 2033 and considering different rates of material recovery and energy recovery from landfill biogas. The results highlighted the significant impacts of landfill disposal, the predominant form of waste disposal in Juiz de Fora. Scenarios with higher material recovery rates performed better in terms of avoided GHG emissions. Furthermore, the study reinforced the importance of using modeling and impact assessment tools for decision-making and defining viable technological pathways for environmentally sound MSW management.

Keywords: life cycle assessment; urban solid waste; environmental impact.

RESUMO

O aumento da população resulta em maior produção de resíduos sólidos urbanos (RSU), elevando os impactos ambientais e na saúde humana. A Política Nacional dos Resíduos Sólidos, instituída pela Lei nº 12.305/2010, exigiu que os municípios repensassem a gestão dos resíduos, priorizando a reciclagem e os tratamentos em relação à disposição final em aterro sanitário. Este estudo teve como objetivo avaliar o impacto ambiental das emissões de gases de efeito estufa (GEE) de diferentes cenários de recuperação dos RSU em Juiz de Fora/MG, utilizando a ferramenta "Calculadora de Emissões de GEE no Manejo de RSU para o Brasil", fundamentada na metodologia de Avaliação do Ciclo de Vida (ACV). Foram avaliados quatro cenários, considerando características de geração de RSU no município para 2017 e 2033, contemplando taxas distintas de recuperação de materiais e aproveitamento energético do biogás do aterro sanitário. Os resultados destacaram os impactos significativos da disposição no aterro sanitário, forma predominante de destinação dos resíduos em Juiz de Fora. Cenários com maiores índices de recuperação de materiais apresentaram melhor desempenho nas emissões evitadas de GEE. Além disso, o estudo reforçou a relevância do uso de ferramentas de modelagem e de avaliação de impacto para a tomada de decisão e definição de rotas tecnológicas viáveis para a gestão ambientalmente adequada dos RSU.

Palavras-chave: avaliação do ciclo de vida; resíduos sólidos urbanos; impacto ambiental.

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Introduction

Challenges related to human activities and "waste" have emerged since the earliest civilizations, with the formation of the first urban agglomerations and clusters, generating public health risks and environmental impacts (Mendez et al., 2022). Population growth has one of its consequences: increased municipal solid waste (MSW) production, which requires special attention due to its potential impact on the environment and human health. These effects are often associated with a lack of adequate waste management (Venes et al., 2023).

The linear production model, present since industrialization, involves the extraction of raw materials, production, consumption, and disposal. This model assumes a steady decline in natural resources and is characterized by excessive consumption and planned obsolescence, resulting in increased waste generation (Chandrappa and Das, 2024). In Brazil, the National Solid Waste Policy (PNRS), established by Law No. 12,305/2010 (Brasil, 2010), established a regulatory framework for solid waste management. The instrument prioritizes solid waste management and disposal, following this order of priority: non-generation, reduction, reuse, recycling, treatment, and environmentally appropriate final disposal of waste, to minimize adverse environmental impacts and maximize resource efficiency (Guabiroba et al., 2023). The PNRS also encourages the use of technologies aimed at energy recovery from MSW, once their technical and environmental feasibility has been proven.

Solid waste management in Brazil has advanced with Federal Decrees No. 10,936/2022 (Brasil, 2022a) and No. 11,043/2022 (Brasil, 2022b) and the National Solid Waste Plan (Planares). These instruments aim to promote the transition from a linear waste management system to a circular model, contributing to the climate agenda (Santiago et al., 2023).

The waste sector was responsible for approximately 91.3 million tons of carbon dioxide equivalent (t CO_2 e) in 2023, representing about 4% of the country's total greenhouse gas (GHG) emissions. Of this total, 65% is related to the final disposal of solid waste (SEEG, 2023).

Activities such as recycling and energy recovery are associated with other sectors. Therefore, national inventories based on the Intergovernmental Panel on Climate Change (IPCC) partially reflect the contribution of waste management to mitigating GHG emissions (Giegrich, 2021).

Given the considerable volume of waste generated and its contribution to the country's total GHG emissions, municipalities face challenges in selecting the most appropriate options for MSW management. As a result, they often adopt measures without careful technical analysis, prioritizing financial considerations.

Thus, the objective of this study is to assess the environmental impact of GHG emissions under different scenarios and technological alternatives applicable to MSW management, based on a case study of a large Brazilian municipality (Juiz de Fora, Minas Gerais). This study aims to obtain results that will assist in decision-making and establish strategies for environmentally sound and sustainable management of municipal solid waste.

Methodology

The study was conducted by collecting data on MSW generation and composition in Juiz de Fora, Minas Gerais, using information from the Plano Municipal de Gestão Integrada de Resíduos Sólidos (PMGIRS), provided by the Department of Urban Planning. Based on this data, different scenarios for MSW management were developed, considering different rates of material recovery, selective collection, and energy recovery from landfills' biogas. These scenarios were analyzed using the tools "GHG Emissions Calculator for MSW Management" and "Technological Routes and Costs Tool for MSW Management," developed by the Federal Government.

The methodology is organized into three main parts: a characterization of the study area, including information about the municipality and data on MSW generation and composition; a description of the tools used to analyze emissions, highlighting their operation, advantages, and limitations; and the construction and analysis of scenarios, detailing the criteria adopted to define management strategies and the indicators evaluated in each situation.

To characterize the study area, data from "Product 2 — Municipal Characterization" of the PMGIRS were used to define the analyzed area. Information from "Product 3 — Participatory Municipal Diagnosis" provided an overview of the MSW collected in the municipality, including gravimetric composition and waste generation.

Characterization of the study area

Located in the southeastern part of Minas Gerais, the municipality of Juiz de Fora had a population of approximately 558,137 residents in 2017, the base year used in the PMGIRS, which provides official data for analyzing waste generation and composition. Its area covers about 1,429.875 km², representing 0.24% of the state's territory. Juiz de Fora is situated in the microregion of the same name, which is part of the Zona da Mata mesoregion (Figure 1) (PJF, 2020).

The area was studied using secondary data from the Municipal Waste Management System (PMGIRS) of Juiz de Fora. Data on the population served by collection services for undifferentiated household waste (waste generated at homes that hasn't been separated for recycling or composting) and selective collection and urban cleaning services provided by the municipal government were used. Additionally, data on the gravimetric composition of household MSW were obtained from municipal analyses available in PMGIRS.

Analysis tools: greenhouse gas emissions calculator for municipal solid waste management

The tools used in this study were developed by the Cooperation for Climate Protection in Urban Solid Waste Management — ProteGEEr, coordinated in Brazil by the Ministry of Integration and Regional Development in partnership with the German Cooperation for Sustainable Development. They jointly developed the "Toolkit for Municipal Solid Waste Management" to improve sustainable MSW management in Brazilian municipalities. These tools are available free of charge on the program's website in Excel spreadsheet format, accompanied by explanatory manuals that guide completion and interpretation of results. The primary tool adopted in this study was the "Greenhouse Gas (GHG) Emissions Calculator for Solid Waste (MSW) Management in Brazil," designed to assist in waste management decision-making based on its impact on GHG emissions. Before entering data into the calculator mentioned above, the "Routes and Costs" tool was used. This step defines the route the waste takes from the generator to the landfill. The "Mass Balance" section was used to simulate current or future MSW management options. Specifically, this part of the tool is designed to select the technologies that will be part of these routes. Based on this selection, it estimates the quantities sent to each unit, the byproducts and waste generated in each process, evaporation losses, and the final mass diverted from the landfill. In the "GHG Output" tab, the mass balance data summary for the evaluated route was used as input data in the "Greenhouse Gas (GHG) Emissions Calculator for Solid Waste Management (MSW) in Brazil" tool. The credits reported by the tool correspond to avoided emissions, calculated considering the replacement of virgin raw materials or fossil fuels with recycled or energy-efficient waste.

The tool enables the comparison of up to four different waste management scenarios using the same waste quantity. Therefore, this work included two analyses: BASE/17, based on the 2017 waste quantities; and the BASE/33, PMGIRS/33, and PLANARES/33 scenarios, which estimate waste for 2033. This structure enabled the comparison between four distinct scenarios, allowing for the assessment of both the current situation and future projections for municipal solid waste management. To calculate GHG emissions from MSW management, the tool uses the Life Cycle Assessment (LCA) methodology for the global warming category, with results expressed in carbon dioxide equivalent (CO2e). The emission factors adopted follow the IPCC's Fifth Assessment Report (AR5). The Global Warming Potential for methane is 30 for fossil methane and 28 for renewable methane, calculated over a 100-year time horizon.

Note that the study above does not represent a complete LCA, as it only considers the potential impact on global-scale warming. However, it provides an approximation of GHG emissions from different technological waste management strategies, representing a valuable tool for guiding decision-making. Among the tool's main features are its ease of form completion, adaptation to the Brazilian context, ability to simulate different management scenarios, and use of emission factors aligned with the IPCC. Furthermore, all results incorporate emissions inherent to the process itself as well as the energy consumption utilized to operate it. Nonetheless, emissions resulting from waste collection were not taken into account, as they are presumed to be within a comparable range across each scenario.

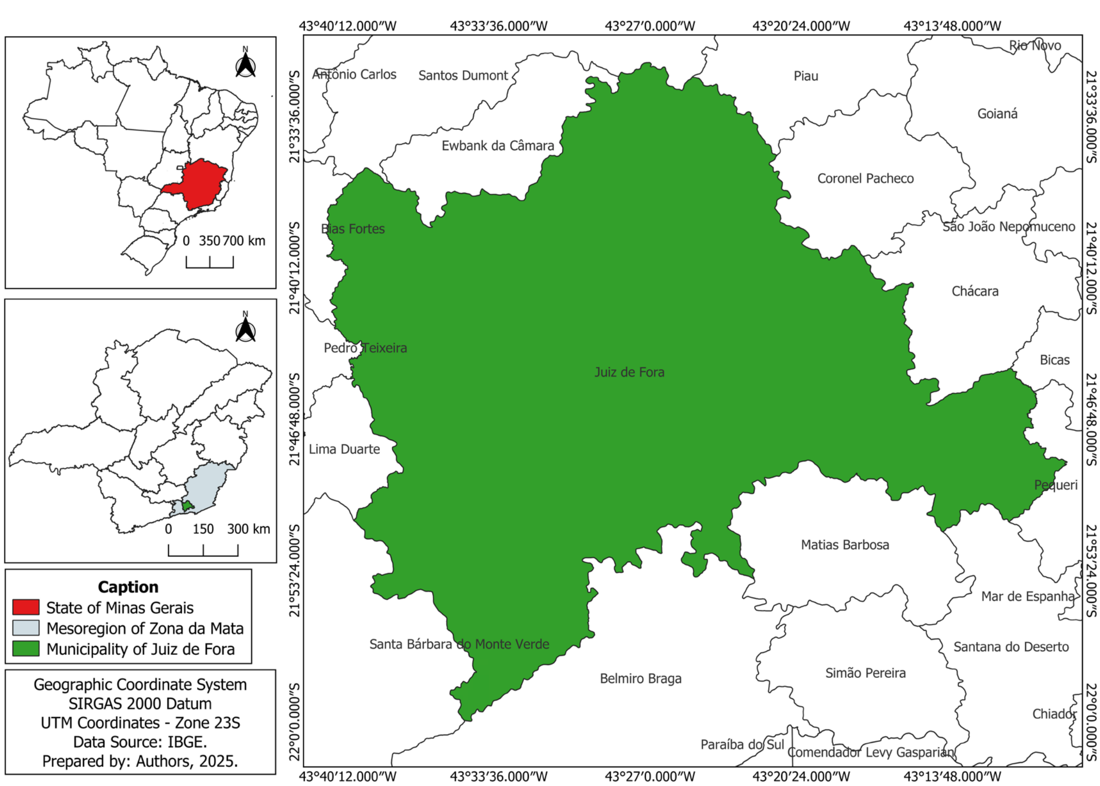


Figure 1 – Location map of the municipality of Juiz de Fora.

Systematization of scenarios

The scenarios were defined to compare different perspectives on the evolution of municipal waste management. The baseline scenario (BASE/17) adopted the 2017 waste management system, as described in the PMGIRS. Three prospective scenarios for 2033 were also developed: BASE/33, which considers the increase in waste generation while maintaining the MSW management system; PMGIRS/33, which incorporates the goals established in the Municipal Plan; and PLANARES/33, which aligns with national guidelines. Thus, the development criteria involved: i. using official data available in current plans, ii. adopting the waste generation projection through 2033, and iii. evaluating alternatives that represent both the continuation of current practices and desired advances in accordance with national and municipal guidelines. Figure 2 provides a summary flowchart for each scenario.

The analysis of all scenarios focused on waste from Juiz de Fora sent to the landfill. The final evaluation highlighted the scenarios with the lowest GHG emissions.

Scenario proposals

In the absence of specific information regarding the municipality, data based on literature surveys and the tool's predefined standards (default), known as the "Brazil Standard," developed by the ProteGEEr Program's consulting team (Paula and Reichert, 2021), were used.

Over the years, research on the behavior of GHGs in relation to CO_2 has updated the equivalence factors for emissions. In the GHG Emissions Calculator for Waste, the most recent factors for methane and nitrous oxide were primarily used, but in some cases, older data were incorporated. Priority was given to information specific to Brazil, followed by regional and global data, which are adapted to reflect local characteristics. Table 1 summarizes the parameter values adopted in all scenarios.

The final disposal of waste in soil contributes to increased global warming due to methane emissions resulting from anaerobic degradation (Kumari and Raghubanshi, 2023). The IPCC guide was used to calculate these landfill emissions. The calculator assumed that all methane is released in the year the waste is generated. Although the gas collection efficiency can be adjusted within the calculator, it is imperative to adopt a conservative approach owing to the potential deficiencies throughout the landfill's lifetime. According to the IPCC, methane capture can range from 9% to over 90%. The efficiency measurements considered in a study by Bian et al. (2021) indicated that 70% of methane was utilized for energy production purposes. However, in all scenarios, a biogas capture efficiency of 30% was adopted, which is a more conservative approach. It is worth noting that since it was not possible to confirm the amount of gas treated and used in the landfill, a scenario was chosen in which 50% is burned in flares and 50% is used for energy generation. Table 2 provides a brief description of the proposed scenarios.

Results and discussion

Composition of Municipal Solid Waste in Juiz de Fora

In 2017, household waste collection served 99.65% of the total population, including 100% of the urban population. Selective waste collection, operated by the municipal authority in partnership with two waste picker associations, reached approximately 62% of the population. Unsorted household waste and refuse were disposed of at a landfill, operated under a public concession, located approximately 20 km from the city center.

The municipal authority is also responsible for urban cleaning services, including sweeping, weeding, mowing, and corrective cleaning in all neighborhoods, as well as maintaining riverbanks and streams. Waste from these activities is sent directly to the landfill without any prior treatment. To understand the makeup of household solid waste in Juiz de Fora, the municipality conducted a gravimetric analysis from May to August 2015 (Figure 3).

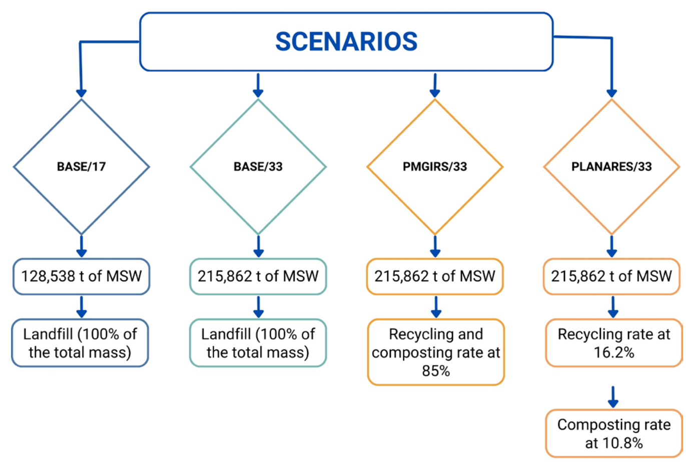
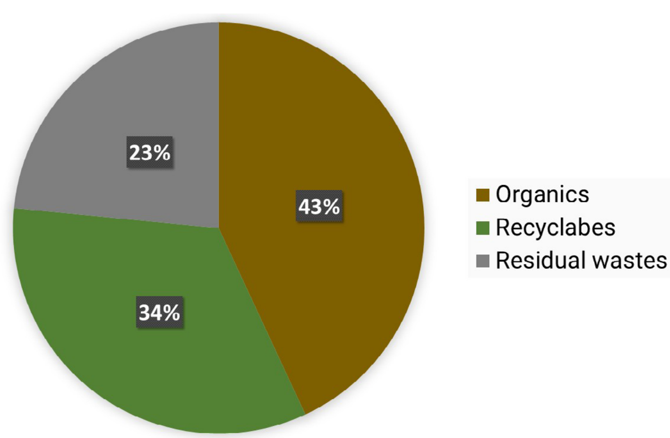


Figure 2 – Flowchart of proposed scenarios.



Source: adapted from PJF (2020).
Figure 3 – Gravimetric composition of household solid waste in the municipality of Juiz de Fora.

Waste under public responsibility, including unsorted household solid waste, dry household solid waste, and urban cleaning waste, represented just over 15% of the total waste generated in the municipality (PJF, 2020).

For reference on the quantity of household solid waste generated in the municipality, the PMGIRS adopted 2017 as the baseline year, when 122,782 tons of waste were generated in the municipality. In addition, approximately 1,263 tons per year were selectively collected in the municipality and sent to associations of recyclable material collectors.

Based on the gravimetric analysis of household solid waste, it was estimated that in 2017, 169.49 tons of organic waste and 131.75 tons of dry waste were disposed of daily in the landfill (PJF, 2020). It should be noted that, at the time, there was no selective collection of organic household waste.

Other urban cleaning services, such as street sweeping, tree cutting and pruning, weeding, and mowing, collected a total of 4,389 tons annually (PJF, 2020).

The PMGIRS (Municipal Plan for Urban Waste Management) sets 2033 as the final target date for implementing its goals and estimates MSW generation at 215,862 tons for that year, considering data from April 2010, when the landfill began operating, to April 2018 (PJF, 2020). Based on these estimates, the projected population for 2033 is 599,053 inhabitants, resulting in a per capita MSW generation of approximately 0.357 tons/inhabitant/year. For comparison, in 2017, with a population of 558,137 inhabitants and a total generation of 122,782 tons of MSW, per capita generation was approximately 0.220 t/inhabitant/year. Table 3 presents the quantities of this waste, in tons per year, for 2017 and the amount estimated by PJF (2020) for 2033.

Analysis of waste management scenarios

BASE/17

In the BASE/17 scenario, 1.5 tons/day of waste are recovered, while 410.5 tons/day are disposed of in landfills, representing 0.4 and 99.6%, respectively (Figure 4A). Figure 4B illustrates the GHG emissions from recycling and biological treatment, as well as landfill disposal. It is important to note that the calculator considers recycled waste as dry and organic waste that is reused. Waste disposal refers to the treatment and final disposal methods adopted, while total MSW treatment is the sum of recycled waste and waste disposal.

The debit values (generated emissions) and net values (generated emissions minus avoided emissions) present similar results. This similarity was influenced by the relatively low amount of recycled material in this scenario. Thus, although recycling helps avoid emissions, its contribution is still limited compared to the system's total emissions.

Emissions from waste disposal in landfills contribute most to the environmental impact of climate change in this scenario. Studies such as those by Iqbal et al. (2019) and Bian et al. (2022) corroborate that the landfill alternative has the greatest impact on GHG emissions.

These results highlight the importance of evaluating sustainable alternatives for waste management. Proposed scenarios involving the recovery of recyclable and organic waste showed potential for reducing GHG emissions from MSW management (Luiz and Suski, 2021; Junqueira et al., 2022).

BASE/33

Figure 5A illustrates the GHG emissions generated and avoided for the BASE/33 scenarios. As in the BASE/17 scenario, 0.4% of the waste is recovered, and 99.6% is sent to landfill, with the amount of MSW estimated for 2033 (215,862 t) as predicted in the PMGIRS (PJF, 2020). Figure 5B represents the greenhouse gas emissions from recycling, biological treatment, and landfill disposal.

The similar debit and net values in the BASE/33 scenario, like in the BASE/17 scenario, are due to the low proportion of recycled material. Results from similar studies have shown a gradual reduction in GHG emissions as new MSW treatment alternatives are included instead of complete landfill disposal (Iqbal et al., 2019; Luiz and Suski, 2021; Junqueira et al., 2022).

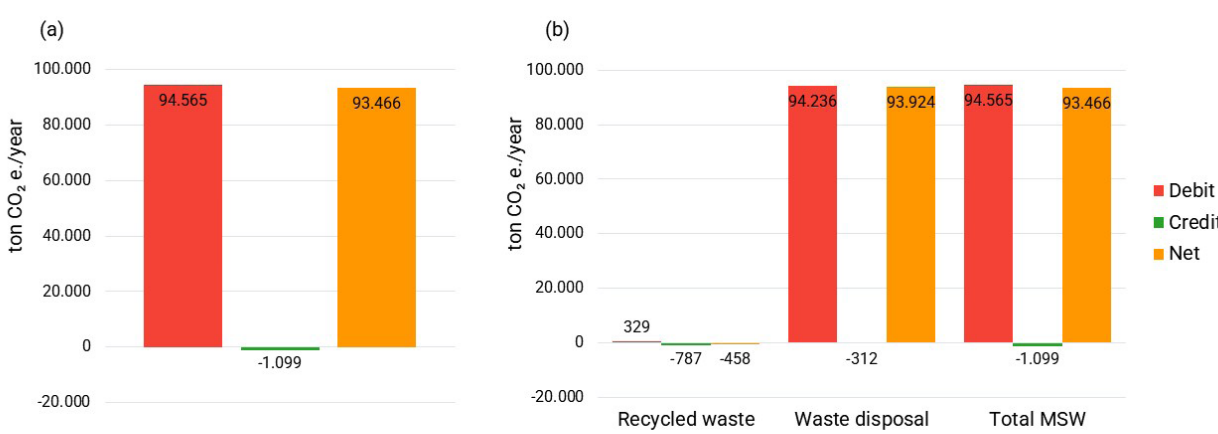


Figure 4 – (A) Summary of greenhouse gas emissions and (B) greenhouse gas emissions from recycling, biological treatment, and waste disposal in t CO_2 e./year for the BASE/17 scenario.

As in the previous scenario, there is a need to implement actions that increase the recycled mass of dry and organic waste, repurposing the large amounts of waste sent to landfills.

PMGIRS/33

The PMGIRS/33 scenario considered the proposed alternative for managing MSW from the PMGIRS: improving material segregation at the source and increasing the amount of waste sent to sorting and recycling units. The strategies proposed to the PJF aim to ensure dry and organic waste collection services reach 100% of the population; recover at least 85% of dry waste by 2033; recover at least 85% of organic waste; and segregately collect 34% of the waste from each urban cleaning activity (PJF, 2020).

In this scenario, 49.5% of the waste produced was recovered through recycling and composting processes. There was a 17.1% loss in mass due to evaporation during composting, and 33.4% of the total generated waste was sent for final disposal in a landfill. Figure 6A shows that credits exceeded debits, resulting in a negative net emissions value. This highlights the significant role of the proposed actions, such as source separation, recycling, and composting, in reducing GHG emissions, as shown in Figure 6B.

Similarly, a study in Varginha, Minas Gerais, Brazil, conducted by Souza et al. (2019), concluded that recycling was the most effective practice for reducing GHG emissions, providing the greatest energy gains and emissions removal among the management practices analyzed. In another context, Dangi et al. (2023) analyzed solid waste management in Kathmandu, Nepal, and found that organic waste composting represents the most efficient strategy for reducing GHG emissions. This is due to the large amount of organic waste in the city, which, when composted, significantly reduces global warming potential and operating costs. In a case study in Florianópolis, Santa Catarina, Brazil, Luiz and Suski (2021) observed a gradual reduction in GHG emissions when scenarios prioritize the use of recyclables and organics. This approach reduces the need for landfills and confirms that alternative treatments are more environmentally appropriate.

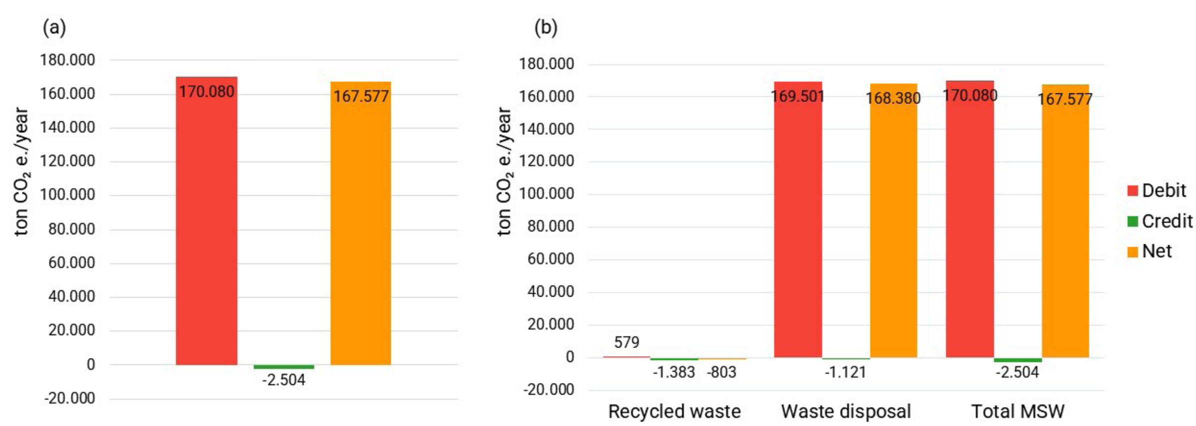


Figure 5 – (A) Summary of greenhouse gas emissions and (B) greenhouse gas emissions from recycling, biological treatment, and waste disposal in t CO_2 e./year for the BASE/33 scenario.

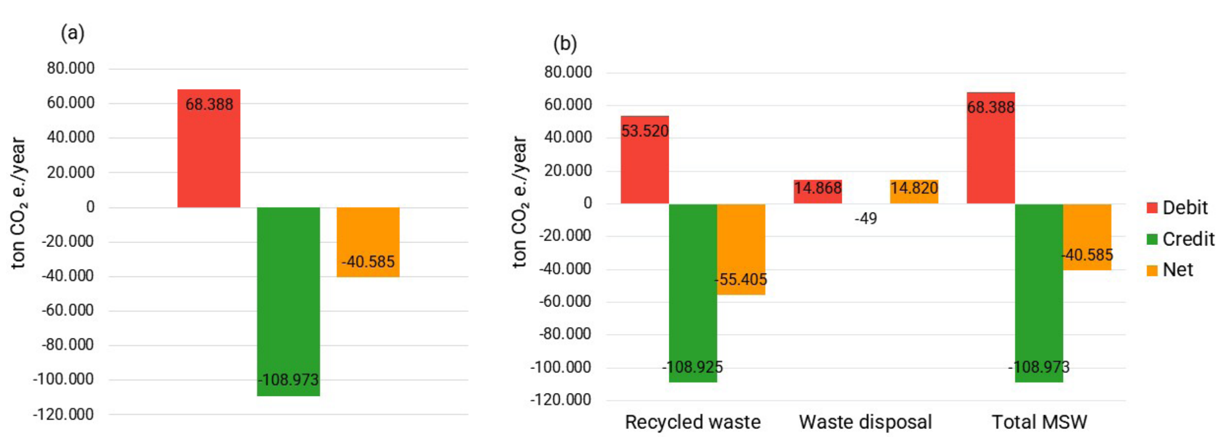


Figure 6 – (A) Summary of greenhouse gas emissions and (B) greenhouse gas emissions from recycling, biological treatment, and waste disposal in t CO_2 e./year for the PMGIRS/33 scenario.

PLANARES/33

In this scenario, the Planares (Brasil, 2022) considered targets for the Southeast region of the country (recovery of 16.2% of dry recyclables and 10.8% of the organic fraction, relative to the total MSW mass) with the same amount of MSW collected in 2033. Therefore, the majority (71.9%) of the waste generated would be sent to the landfill, while 23.7% would be recovered through recycling and composting, and 4.4% would be lost due to composting. Figure 7A shows the GHG balance for this scenario, while Figure 7B illustrates GHG emissions from recycling, biological treatment, and landfill disposal.

Credits in this scenario significantly impact reducing GHG emissions, highlighting the importance of measures to promote sustainability. These values indicate that sending waste to landfills generates a significant amount of GHG emissions.

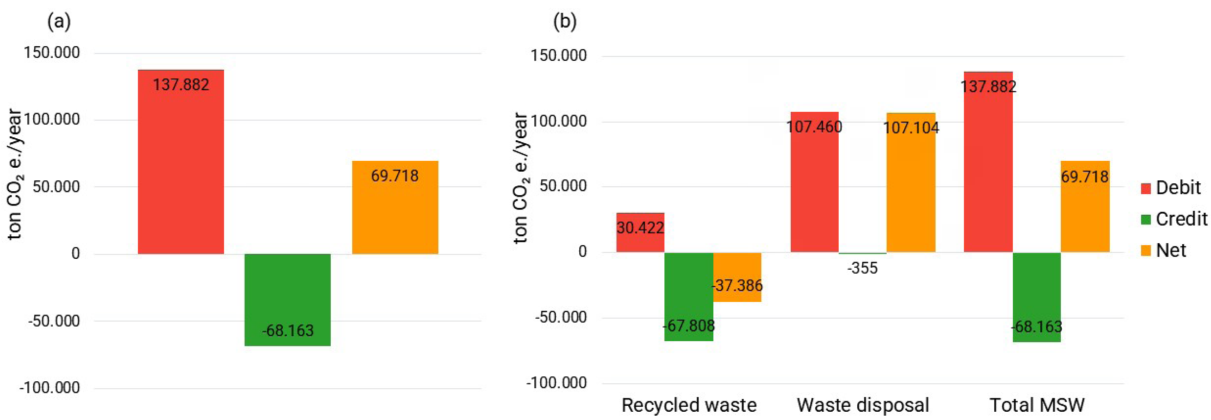


Figure 7 – (A) Summary of greenhouse gas emissions and (B) greenhouse gas emissions from recycling, biological treatment, and waste disposal in t CO_2 e./year for the PLANARES/33 scenario.

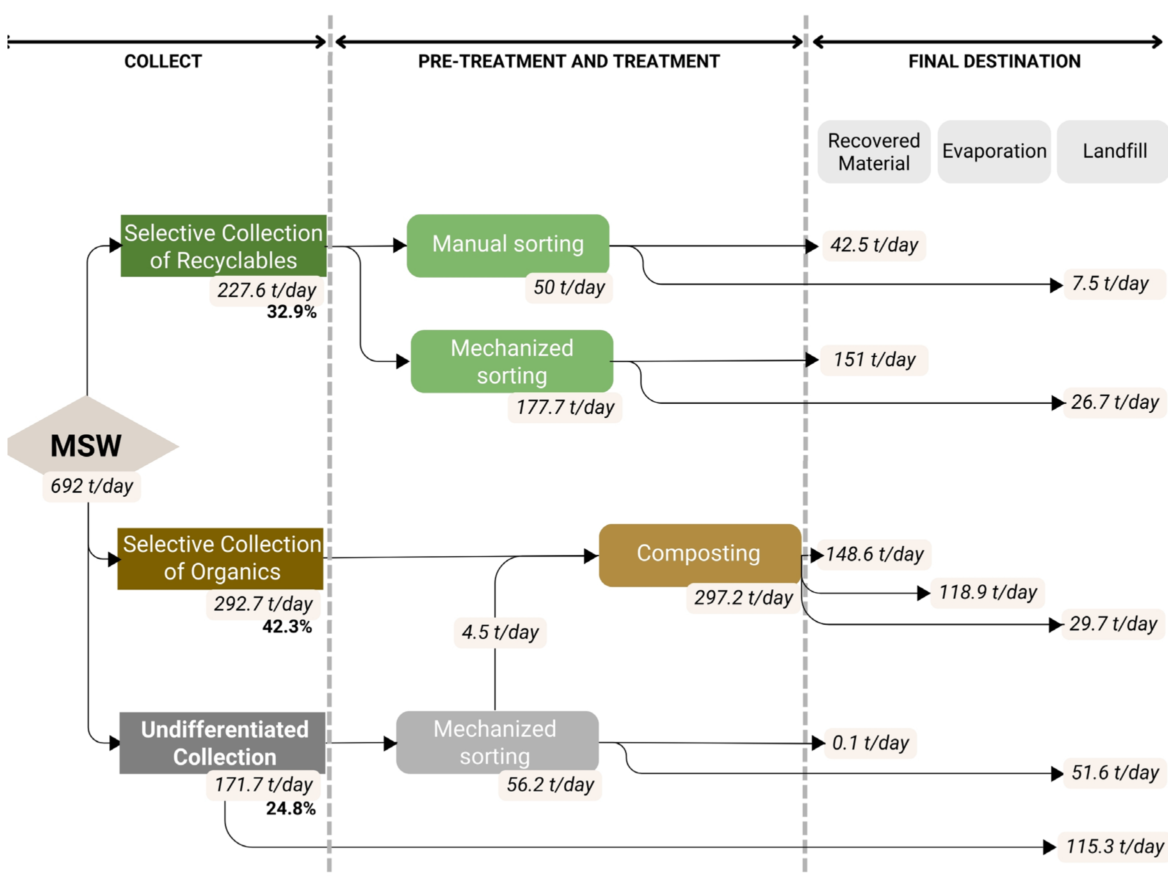


Figure 8 – Mass flow of the PMGIRS/33 scenario.

Table 1 – Summary of adopted parameters.

Parameter	Adopted value	Reference
Biogas capture efficiency	30%	Min. 10% and max. 50%: Giegrich (2021); Min. 9% and max. 90%: Paula and Reichert, 2021.
Energy potential of biogas	16.8 MJ/Nm³	Paula and Reichert (2021).
Efficiency in electricity generation	35%	Paula and Reichert (2021).
Participation of methane in the composition of biogas	60%	(75–80%) Mateus et al. (2020).

Table 2 – Description of the proposed proposals.

Scenario	Description	Waste management steps	
BASE/17	Base scenario of Juiz de Fora, referring to the year 2017	Collection of selective waste in relation to the total waste fraction	1%
		Collection of unsorted waste in relation to the total waste fraction	99%
		Sorting of selective waste	100%
		Recycling of selective waste collection	37%
		Final disposal of the total waste fraction, considered rejects, in a landfill	99.6%
BASE/33	Baseline scenario for Juiz de Fora, with estimated waste generation for 2033	Collection of selective waste in relation to the total waste fraction	1%
		Collection of unsorted waste in relation to the total waste fraction	99%
		Sorting of selective waste collection	100%
		Recycling of selective waste collection	37%
		Final disposal of the total waste fraction, considered rejects, in a landfill	99.6%
PMGIRS/33	Scenario with selective and mixed waste sorting and composting (PMGIRS Proposal); estimated waste generation for 2033	Collection of 100% of selective waste	100%
		Collection of unsorted waste	100%
		Sorting of selective and unsorted waste	100%
		Recycling of selective waste	85%
		Composting of organic matter	85%
		Final disposal of waste in a landfill	33.4%
PLANARES/33	Scenario with selective and mixed waste sorting and composting, taking into account PLANARES percentages; estimated waste generation for 2033	Collection of selective waste	70.9%
		Collection of unsorted waste	100%
		Sorting of selective and unsorted waste	100%
		Recycling of selective waste, in relation to the total mass of MSW	16.2%
		Composting of organic matter in relation to the total mass of MSW	10.8%
		Final disposal of waste in a landfill	71.9%

By encouraging and promoting recycling and composting practices, a significant portion of the waste can be diverted from landfills, thus minimizing CH_4 emissions. Therefore, by directing a substantial portion of the waste to recycling and composting, the municipality can substantially reduce GHG emissions (Souza et al., 2019; Luiz and Suski, 2022; Dangi et al., 2023).

Comparison between scenarios

Table 3 presents the total, avoided, and net GHG emissions from landfill disposal observed in each scenario.

In the BASE/17 and BASE/33 scenarios, avoided emissions occur due to the use of CH_4 produced in the landfill for electricity generation (Chen et al., 2024). The results show that landfill disposal is the primary source of environmental impact on climate change in solid waste management (Iqbal et al., 2019; Bian et al., 2022).

In the PMGIRS/33 scenario, there is a significant reduction in landfill emissions due to the implementation of targets established by the municipality's PMGIRS, which aim to achieve 85% recovery rates for waste generated through recycling and composting.

Composting is a key treatment alternative for reducing the amount of waste sent to landfills, leachate generation, and methane emissions. Aligned with the Política Nacional de Resíduos Sólidos. (PNRS), which prioritizes recycling and treatment, composting helps reduce GHG emissions and generate carbon credits by avoiding the disposal of organic waste in landfills. A case study in Rio de Janeiro showed that composting reduced CH_4 emissions by 83.5%, reinforcing the importance of composting for low-carbon waste management (Cartoza et al., 2022).

The efficiency of biogas energy recovery depends on the amount of organic matter sent to landfills, so reducing this matter lowers the potential for energy generation. Therefore, composting can decrease environmental impact per landfill area, but it may also reduce energy recovery from CH4. Consequently, it is crucial to consider both aspects, taking into account the objectives, demands, and structures in each case (Dai-Prá et al., 2018). Ruoso et al. (2022) assessed that the solid waste sector has significant potential to reduce GHG emissions by 78% by utilizing methane produced in landfills to generate biogas energy.

In the BASE/33 scenario, compared to the BASE/17 scenario, an increase of approximately 80% in GHG emissions was observed, mainly due to the increase in waste generated. In the PMGIRS/33 scenario, this decrease was approximately 150%, while in the PLANARES/33 scenario, it was 25%. This difference can be attributed to the lower recycling of materials and the lack of treatment of organic waste in the BASE/33 scenario compared to the alternative scenarios, as mentioned in the study by Costa et al. (2019).

The PMGIRS/33 scenario is notable for achieving the highest emission reductions by emphasizing reduction, reuse, and recycling. It integrates waste management steps to enhance material reuse and lower environmental impact. shows the mass flow of waste in this scenario at the different stages of the process, from collection to treatment and final disposal. The fractions destined for recycling and composting directly contribute to reducing the volume of waste sent to landfills.

Table 3 – Composition of urban solid waste (municipal solid waste) generated in the municipality of Juiz de Fora.

Solid waste generation	2017 t/year	2033 t/year
Selective collection	**1,263**	**2,126**
Household solid waste		
Organics waste	52,882	88,807
Dry waste	41,108	69,033
Waste tailings	28,792	48,352
Total	**122,782**	**206,192**
Urban cleaning waste		
Sweeping	3,028	5,085
Tree cutting and pruning	103	173
Weeding debris	1,361	2,286
Total	**4,492**	**7,544**

Source: adapted from PJF (2020).

Table 4 – Total emissions, avoided emissions, and net emissions (t CO_2 e./year) and specific emissions (kg CO_2 e./t of MSW) of GHG from final waste disposal.

Scenario	Total emissions	Avoided emissions	Net results	Specific emissions
BASE/17	94,236	−312	93,924	0.73
BASE/33	169,501	−561	168,940	0.78
PMGIRS/33	14,868	−49	14,820	0.07
PLANARES/33	107,460	−355	107,104	0.50

According to Olivo et al. (2021), waste recovery is essential because most waste can be treated and reused, thereby reducing environmental impacts. With the use of appropriate technologies, waste previously considered an environmental liability can become an asset for local governments.

The integrated waste treatment approach in the PMGIRS/33 and PLANARES/33 scenarios, which combines recycling, composting, and final disposal in a landfill, results in the lowest environmental impacts in terms of GHG emissions. This highlights the importance of integrated and sustainable waste management strategies focused on reducing environmental impacts and fighting global warming. Therefore, it is crucial that managers first evaluate different technological approaches for managing municipal solid waste, following the hierarchy established by the PNRS and complying with applicable legislation.

Achieving the 85% recycling and composting target proposed in the PMGIRS is a challenge that requires investment in infrastructure, awareness, and active public involvement. More ambitious targets can encourage a sustainable approach, stimulate innovation, promote economic and social growth, and help protect the environment and improve quality of life, aligning with the sustainable development goals.

The PLANARES/33 scenario, aligned with the Planares targets, shows a significant reduction in GHG emissions compared to the baseline scenario, reinforcing the importance of recycling and composting. Planares targets are designed based on the country's current situation, available resources, and waste management challenges. They are realistic, recognizing that significant changes require time, resources, and coordinated efforts (Brasil, 2022).

According to Olivo et al. (2021), for local governments to achieve integrated and sustainable waste management goals, practical actions must be adopted, focusing on standardization, oversight, social mobilization, and infrastructure expansion. It is essential to develop manuals and standards that guide the reduction, segregation, and reuse of waste. Additionally, promoting public participation through environmental education programs, aimed primarily at schools and organized groups, is crucial.

Conclusion

The study analyzed the waste management model adopted in the municipality of Juiz de Fora, Minas Gerais. This model includes a control system implemented by the public administration, providing greater internal knowledge and potential for advancements in the sector.

The BASE/17 and BASE/33 scenarios presented the highest net GHG emissions, with 93,466 t CO_2 e./year and 167,577 t CO_2 e./year, respectively, due to the complete disposal of MSW in landfills. The PMGIRS/33 scenario presented a net balance of −40,585 t CO_2 e./year, demonstrating the reduction in emissions provided by the reuse of recyclable and organic waste. The PLANARES/33 scenario, with net emissions of 69,718 t CO_2 e./year, demonstrated the importance of implementing recycling and composting strategies. The results indicate that MSW management should consider the final disposal of waste, including collection, transportation, and treatment processes, while striving for greater environmental efficiency. The definition of management strategies should integrate environmental, economic, and social aspects, in accordance with the principles of sustainable development.

Future research can expand the analysis to include different recovery fractions, treatment options, and integrated assessments of social, economic, and environmental impacts, contributing to a more comprehensive understanding of solid waste management alternatives in the municipality.

Authors' Contributions

Miranda, T.S.: conceptualization, data curation, formal analysis, methodology, writing – original draft. **Gomes**, F.B.R.: writing – review & editing. **Paula,** V.R.: Supervision, validation, writing – review & editing. **Benhami**, V.M.L.: writing – review & editing. **Castro**, S.R.: Supervision, writing – review & editing.

References

Bian, R.; Chen, J.; Li, W.; Shi, W.; Lin, Y.; Chai, X.; Sun, Y., 2021. Methane emissions and energy generation potential from a municipal solid waste landfill based on inventory models: A case study. Environmental Progress & Sustainable Energy, v. 40 (5), e13654. https://doi.org/10.1002/ep.13654.

Bian, R.; Chen, J.; Zhang, T.; Gao, C.; Niu, Y.; Sun, Y.; Zhan, M.; Zhao, F.; Zhang, G., 2022. Influence of the classification of municipal solid wastes on the reduction of greenhouse gas emissions: A case study of Qingdao City, China. Journal of Cleaner Production, v. 376, 134275. https://doi.org/10.1016/j.jclepro.2022.134275.

Brasil, 2010. Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos, altera a Lei nº 9.605, de 12 de fevereiro de 1998; e dá outras providências. Brasília, DF: Presidência da República (Accessed march, 10, 2023) at:. https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm.

Brasil, 2022a. Decreto nº 10.936, de 12 de janeiro de 2022. Regulamenta a Lei nº 12.305, de 2 de agosto de 2010, que institui a Política Nacional de Resíduos Sólidos. Brasília, DF: Presidência da República (Accessed march, 10, 2023) at:. https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/d10936.htm.

Brasil, 2022b. Decreto nº 11.043, de 13 de abril de 2022. Aprova o Plano Nacional de Resíduos Sólidos. Brasília, DF: Presidência da República (Accessed march, 10, 2023) at: https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/d11043.htm.

Catorza, C.F.; Van Elk, A.G.H.P.; Passos, L.H.S., 2022. Potential of carbon credits generation from organic waste composting of large generators: an alternative to the final disposal in sanitary landfills. Revista Brasileira de Ciências Ambientais (RBCIAMB), v. 57 (2), 206-214. https://doi.org/10.5327/Z2176-94781121.

Chandrappa, R.; Das, D.B., 2024. Waste quantities and characteristics. In: Chandrappa, R.; Das, D.B. (Eds.), Solid Waste Management: Principles and Practice. Cham, Springer International Publishing, pp. 47-87. https://doi.org/10.1007/978-3-031-50442-6_2.

Chen, Z.; Kurniawan, T.A.; Yap, P., 2024. Integrating leachate treatment into circular economy landfill practices for nutrient, energy, and material (NEM) recovery and climate change mitigation. Journal of Water Process Engineering, v. 68, 106524. https://doi.org/10.1016/j.jwpe.2024.106524.

Costa, G.; Lieto, A.; Lombardi, F., 2019. LCA of a Consortium-based MSW management system to quantify the decrease in environmental impacts achieved for increasing separate collection rates and other modifications. Sustainability, v. 11 (10). https://doi.org/10.3390/su11102810.

Dai-Prá, L.B.; Moraes, C.A.M.; Gomes, L.P.; Marques, V.M., 2018. Avaliação de ciclo de vida (ACV) aplicada à gestão de resíduos sólidos urbanos (RSU) em aterros: uma revisão. Revista Brasileira de Planejamento e Desenvolvimento, v. 7, n. 3, Edição Especial Fórum Internacional de Resíduos Sólidos, 353-364. https://doi.org/10.3895/rbpd.v7n3.8640.

Dangi, M.B.; Malla, O.B.; Cohen, R.R.H.; Khatiwada, N.R.; Budhathoki, S., 2023. Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – An impact of an incomplete data set. Habitat International, v. 139, 102895. https://doi.org/10.1016/j.habitatint.2023.102895.

Giegrich, J., 2021. Manual da Calculadora de Emissões de GEE para Resíduos: Ferramenta de Cálculo de Emissões de Gases de Efeito Estufa (GEE) no Manejo de RSU para o Brasil: metodologia de avaliação do ciclo de vida (ACV). Cooperação para A Proteção do Clima na Gestão dos Resíduos Sólidos Urbanos – Protegeer (Accessed May 01, 2023) at:. https://www.gov.br/cidades/pt-br/acesso-a-informacao/acoes-e-programas/saneamento/protegeer/copy_of_ManualdaFerramentadeGEE_02.08.2021.pdf.

Guabiroba, R.C.S.; Jacobi, P.R.; Abegão, L.H.; Besen, G.R., 2023. Sustainability performance evaluation of municipal selective collection systems applied to a case study. Revista Brasileira de Ciências Ambientais (RBCIAMB), v. 58 (1), 1-10. https://doi.org/10.5327/Z2176-94781482.

Iqbal, A.; Zan, F.; Liu, X.; Chen, G.-H., 2019. Integrated municipal solid waste management scheme of Hong Kong: A comprehensive analysis in terms of global warming potential and energy use. Journal of Cleaner Production, v. 225, 1079-1088. https://doi.org/10.1016/j.jclepro.2019.04.034.

Junqueira, H.S.; Medeiros, D.L.; Cohim, E., 2022. Gerenciamento de resíduos sólidos urbanos de Feira de Santana: demanda energética e pegada de carbono. Engenharia Sanitaria e Ambiental, v. 27 (1), 125-139. https://doi.org/10.1590/S1413-415220200358.

Kumari, T; Raghubanshi, A.S., 2023. Waste management practices in the developing nations: challenges and opportunities. Waste Management and Resource Recycling in the Developing World, 773-797. https://doi.org/10.1016/B978-0-323-90463-6.00017-8.

Luiz, B.; Suski, C.A., 2021. Avaliação da geração de gases de efeito estufa em diferentes tratamentos de resíduos domiciliares – Estudo de caso em Florianópolis-SC. Metodologias e Aprendizado, v. 4, 89-98. https://doi.org/10.21166/metapre.v4i.1489.

Mateus, S.; Carvalheira, M.; Cassidy, J.; Freitas, E.; Oehmen, A.; Reis, M.A.M., 2020. Two-stage anaerobic digestion system treating different seasonal fruit pulp wastes: Impact on biogas and hydrogen production and total energy recovery potential. Biomass and Bioenergy, v. 141, p. 105694. https://doi.org/10.1016/j.biombioe.2020.105694.

Mendez, G.P.; Mahler, C.F.; Taquette, S.R., 2022. Gestão de Resíduos Sólidos: revisão sistemática de estudos qualitativos. Ciência e Natura, v. 42, e36. https://doi.org/10.36367/ntqr.4.2020.55-66.

Olivo, V.E.; Prietto, P.D.M.; Kork, E.P., 2021. Actions and policy tools for local governments to achieve integrated sustainable waste management. Revista Brasileira de Ciências Ambientais (RBCIAMB), v. 56 (3), 436-444. https://doi.org/10.5327/Z21769478968.

Paula, A.S.; Reichert, G.A., 2021. Manual do Usuário: Ferramenta de Rotas e Custos. Brasília: Cooperação para a proteção do clima na gestão dos resíduos sólidos urbanos – ProteGEEr (Accessed May 01, 2023) at:. https://www.gov.br/cidades/pt-br/acesso-a-informacao/acoes-e-programas/saneamento/protegeer/ferramenta-de-rotas-tecnologicas-e-custos-para-manejo-de-rsu-e-manual-do-usuario-200b/01.ManualdaFerramentaRotaseCustos_jun.2021.pdf.

Prefeitura Municipal de Juiz de Fora (PJF), 2020. Plano Municipal de Gestão Integrada de Resíduos Sólidos de JF (Accessed May 15, 2023) at:. https://www.pjf.mg.gov.br/secretarias/sepur/planos_programas/pmgirs/produtos/index.php.

Ruoso, A.C.; Dalla Nora, M.; Siluk, J.C.M.; Ribeiro, J.L.D., 2022. The impact of landfill operation factors on improving biogas generation in Brazil. Renewable and Sustainable Energy Reviews, v. 154, 111868. https://doi.org/10.1016/j.rser.2021.111868.

Santiago, C.D.; Marotti, A.C.B.; Pugliesi, E.; Gonçalves, J.C., 2023. Política Nacional de Resíduos Sólidos: perspectivas após um decênio de sua promulgação. Desenvolvimento e Meio Ambiente, v. 62, 152-177. https://doi.org/10.5380/dma.v62i0.81833.

Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG), 2023. Análise das emissões brasileiras de gases de efeito estufa e suas implicações para as metas climáticas do Brasil 1970-2022 (Accessed July 01, 2024) at:. https://seeg.eco.br/wp-content/uploads/2024/02/SEEG11-RELATORIO-ANALITICO.pdf.

Souza, A.R.; Silva, A.T.Y.L.; Trindade, A.B.; Freitas, F.F.; Anselmo, J.A., 2019. Análise do potencial de aproveitamento energético de biogás de aterro e simulação de emissões de gases do efeito estufa em diferentes cenários de gestão de resíduos sólidos urbanos em Varginha (MG). Engenharia Sanitária e Ambiental, v. 24 (5), 887-896. https://doi.org/10.1590/S1413-41522019187066.

Venes, H.; Galavote, T.; Rosa, R.A.; Siman, R.R., 2023. "That's (not) Rubbish!" Planning the reverse logistic for recyclable solid waste using a vehicle routing problem: a case study in Vitória/ES. International Journal of Sustainable Development and Planning, v. 18 (7), 2191-2198. https://doi.org/10.18280/ijsdp.180723.