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Geosciences

Greenhouse gas emissions from composting and landfilling of organic waste and their influence on global warming

Emissões de gases de efeito estufa provenientes de compostagem e aterramento de resíduos orgânicos e sua influência no aquecimento global

Glenda Fauth[I], Cássio Aurélio Suski[I], Juliano da Cunha Gomes[I], Débora Souza Alvim[II], Pedro Fernando Wengrzyn dos Passos[I]

[I] Instituto Federal de Educação, Ciência e Tecnologia de Santa Catarina, Florianópolis, SC, Brasil
[II] Universidade de São Paulo, São Paulo, SP, Brasil

ABSTRACT

Climate change is a global challenge, and solid waste management plays an important role in the reduction of greenhouse gas (GHG) emissions. Composting emerges as a solution to reduce emissions, particularly of methane (CH_4), from landfills. However, the composting process also generates GHGs, and its impact on global warming is not yet fully understood. This study aims to assess the impact of GHG emissions from composting on global warming, using the municipality of Garopaba as the case study. The amount of organic waste generated in Garopaba was determined based on official data from the Municipal Basic Sanitation Plan and the State Solid Waste Plan. Between 2017 and 2022, organic waste generation increased by 10.8%, totaling 5,409.01 tons in 2022, the base year of the analysis. Different waste disposal scenarios were analyzed using the GHG Protocol tool, evaluating the impact of the transition from landfills to composting on GHG emissions. The results indicate that the gradual replacing of organic waste disposal from landfills to composting could reduce total GHG emissions up to 88.7%. Finally, the evaluation of the impact of these emissions on global temperature presented a variation with estimated reductions ranging from - 0.00026°C to - 0.00104°C. Although composting results in GHG emission reductions, its direct impact on mitigating global warming is limited, especially on a local scale.

Keywords: Composting; Greenhouse Gases; Global warming

RESUMO

As mudanças climáticas são um desafio global, e o gerenciamento de resíduos sólidos pode ter um papel importante na redução da emissão de gases de efeito estufa (GEE). A compostagem surge como uma solução para reduzir as emissões, especialmente de metano (CH_4), provenientes de aterros sanitários.

No entanto, o processo de compostagem também gera GEE, e seu impacto no aquecimento global ainda não é completamente compreendido. Este estudo visa avaliar o impacto das emissões de GEE da compostagem no aquecimento global, utilizando o município de Garopaba como estudo de caso. A quantidade de resíduos orgânicos gerados em Garopaba foi determinada com base em dados oficiais do Plano Municipal de Saneamento Básico e do Plano Estadual de Resíduos Sólidos. Entre 2017 e 2022, a geração de resíduos orgânicos aumentou 10,8%, totalizando 5.409,01 toneladas em 2022, ano-base da análise. Diferentes cenários de destinação de resíduos foram analisados com a ferramenta GHG Protocol, avaliando o impacto da transição do aterro para a compostagem nas emissões de GEE. Os resultados indicam que, ao substituir gradualmente o envio de resíduos orgânicos de aterros para compostagem, seria possível reduzir as emissões totais de GEE em até 88,7%. Por fim, a avaliação do impacto dessas emissões na temperatura global mostrou uma variação com reduções estimadas entre -0,00026°C e -0,00104°C. Apesar de a compostagem resultar em reduções nas emissões de GEE, seu impacto direto na mitigação do aquecimento global é limitado, especialmente em escala local.

Palavras-chave: Compostagem; Gases de Efeito Estufa; Aquecimento global

1 INTRODUCTION

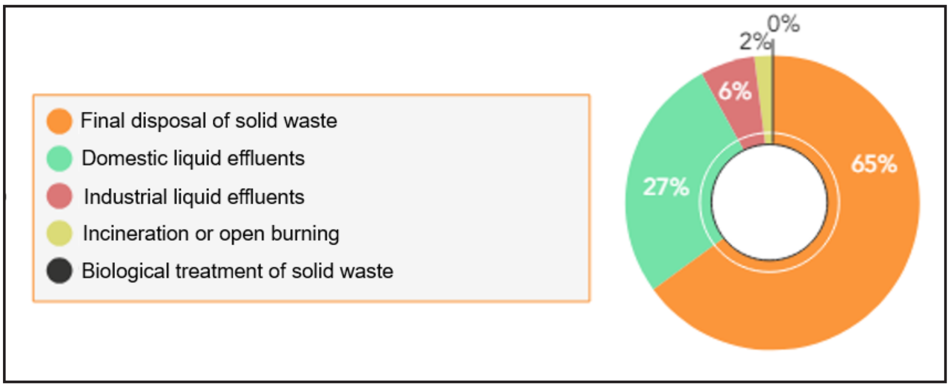
Climate change is an undeniable reality and represents one of the greatest challenges that humanity currently faces. Greenhouse Gas (GHG) emissions increase is the main factor responsible for the global warming observed in recent decades (IPCC, 2021). According to the IPCC (2023), the Earth's surface temperature was 1.1°C higher in 2011-2020 compared to 1850–1900. GHG emissions continued to increase, driven by historical contributions from the unsustainable use of energy and land, as well as humanity's equally unsustainable lifestyle and consumption patterns. The main gases responsible for climate change are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

In Brazil, GHG emissions are distributed across the sectors of Land Use Change and Forestry, Agriculture, Energy, Waste, and Industrial Processes and Product Use (IPPU) (SEEG, 2023; IPCC, 2019). Historically, the primary source of emissions has been Land Use Change and Forestry, accounting for 48% of the national total in 2022, mainly driven by deforestation (SEEG, 2023). Agriculture, which includes both crop production and livestock farming, is responsible for 27% of emissions, reaching a record 617.2 million tons of CO_2e in 2022, a 3.2% increase from 2021 due to livestock production growth (Ortiz; Guimarães, 2022; SEEG, 2023). Combined emissions from deforestation and agriculture represent 75% of Brazil's total GHG emissions, with 90% to 99% of tropical deforestation attributed to agriculture (SEEG, 2023). The Energy sector, the third-largest emitter, contributed 18% of emissions in 2022, while IPPU accounted for 3%, totaling 490.6 million tons of CO_2e, with 44% of these emissions coming from transportation (SEEG, 2023; IPCC, 2019).

Another GHG-emitting activity is solid waste management. In 2022, the waste sector was responsible for the emission of 91.3 million tons of CO_2e in Brazil, accounting for 4% of the country's total GHG emissions, considering methane as the main contributor (SEEG, 2023). The decomposition of organic waste in landfills, for instance, produces methane which is a greenhouse gas 28 times more powerful than carbon dioxide (IPCC, 2013).

In Brazil, the majority of GHG emissions from the waste sector are attributed to the disposal of solid waste in controlled landfills, open dumps, and sanitary landfills (65.5%), followed by domestic wastewater treatment (27%) and industrial wastewater treatment (6%). Incineration, open burning, and composting contribute minimally, as these practices are not widely adopted in the country (SEEG, 2023). Figure 1 illustrates the distribution of emissions in the waste sector.

Figure 1 – Distribution of emissions in the waste sector



Source: Adapted from SEEG (2023)

In this context, the most promising solutions for reducing emissions related to solid waste involve the gradual reduction of organic waste sent to landfills (Brasil, 2021). The Brazilian National Solid Waste Policy (PNRS - Law Nº. 12.305/2010) establishes a legal framework for waste management in Brazil, prioritizing waste reduction, reuse, and recycling before final disposal in landfills (Brasil, 2010). Additionally, the National Solid Waste Plan (Planares - Decree Nº. 11.043/2022) serves as the main instrument of the PNRS and defines strategies to modernize waste management in Brazil, including the elimination of dumpsites by 2024, the recovery of organic waste through biological treatment systems such as composting, and increased recycling efforts (Brasil, 2022).

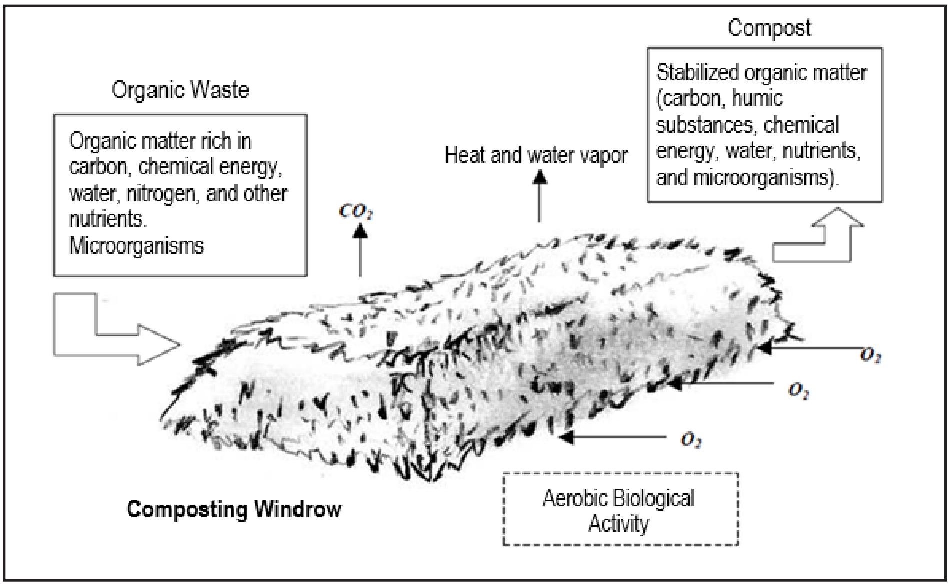
Among the strategies proposed by the PNRS, composting stands out as an environmentally sound method for treating organic waste. As an aerobic process, composting generates significantly lower amounts of methane per ton of organic waste compared to anaerobic treatment methods, such as landfilling (Amlinger; Peyr; Cuhls, 2008). Furthermore, composting not only reduces landfill dependency but also enhances the economic value of waste, aligning with the overarching goals of the PNRS.

The definition of composting may vary depending on the microbiological, agronomic, or environmental engineering perspective. Essentially, it is a biological decomposition process of organic matter that occurs aerobically and thermophilically, meaning it requires oxygen and generates heat, typically reaching temperatures between 50°C and 65°C, with peaks exceeding 70°C (Inácio; Miller, 2009).

There are various composting methods for treating organic waste, ranging from advanced technologies to simpler approaches. Some are designed to handle large volumes of waste, while others are more suitable for small-scale treatment (Santa Catarina State Research and Innovation Support Foundation FAPESC, 2017). Three main characteristics differentiate these methods: the frequency of pile turning, the presence or absence of forced aeration, and whether the material is confined in reactors. Additionally, different strategies may be combined at various stages of the process (Inácio, 2010).

The composting technique aims to create optimal conditions of moisture, oxygen, and nutrients, particularly carbon and nitrogen, to accelerate the decomposition of organic waste safely, preventing the spread of diseases and eliminating pathogens (Brasil, 2017). The biological degradation process utilizes available O_2 to transform the carbon from the organic substrate and obtain energy, releasing CO_2, water, and heat, as illustrated in Figure 2.

Figure 2 – Composting process, considering the static pile method with passive aeration



Source: Adapted from Inácio and Miller (2009)

Under ideal conditions, microorganisms transform organic waste into stabilized organic compost, which enhances soil quality by providing nutrients, stabilizing aggregates, and improving pH. The primary use of organic compost is in horticulture and fruit cultivation, serving as a substrate component for seedling production of vegetables, fruit trees, flowers, and tree species. It can be used in both rural areas and as an agricultural input for urban farming practices (Inácio; Miller, 2009).

The quality of compost may be influenced by several interrelated factors that should be carefully monitored throughout the process. Key aspects include maintaining an appropriate carbon-to-nitrogen (C/N) ratio, regulating temperature and moisture levels, ensuring adequate oxygen supply to support aerobic microbial activity, and allowing sufficient time for maturation. Additionally, monitoring chemical and biological parameters can help prevent contamination by pathogens, heavy metals, and other undesirable compounds. Compliance with technical standards – such as those established by CONAMA Resolution No. 481/2017 – may contribute to ensuring that the final compost is safe and suitable for agricultural or urban use. Attention to these factors can enhance the environmental, sanitary, and agronomic benefits associated with composting.

The composting process, involving carbon-rich materials (organic waste), microorganisms, energy, and water, results in a significant reduction in both the volume and weight of the original material. Carbon loss through CO_2 emissions and substantial moisture evaporation lead to volume reductions of approximately 25–50% and weight reductions ranging from 40–80% (Inácio; Miller, 2009).

The composting process consists of four stages: (1) Initial/Heating Phase, where mesophilic microorganisms decompose organic matter, increasing temperature; (2) Thermophilic Phase, where temperatures exceed 45°C, and thermophilic microorganisms accelerate decomposition; (3) Mesophilic Phase, where resistant substances degrade, leading to temperature reduction; and (4) Maturation Phase, where humic substances form, and microbial activity declines (Inácio, 2010; Brasil, 2017; Epstein, 1997). Considering the Static Pile Method with Passive Aeration (UFSC Method), the total composting time is approximately 120 days, with the initial phase lasting about 4 days, the thermophilic phase around 30 days, the mesophilic phase 60 days, and the maturation phase at least 30 days (Brasil, 2017).

To achieve sustainable development, Inácio and Miller (2009) emphasized that composting will be essential, as it represents the recycling process of nutrients that feed us and the organic matter that keeps soil fertile and productive.

Therefore, it is crucial to improve knowledge and practices around composting, as well as the methods for assessing and monitoring the quality of the waste and compost produced, and its contribution to mitigating GHG emissions.

The objective of this study is to analyze the impact of greenhouse gas (GHG) emissions from composting on global warming, using the municipality of Garopaba as the case study.

2 METHODOLOGY

This study was conducted in the municipality of Garopaba. It is located on the southern coast of Santa Catarina, at a latitude of 28º1’25” South, longitude of 48º36’50” West, and an altitude of 17 meters above sea level. It borders the municipality of Imbituba to the south, Paulo Lopes to the north and west, and the Atlantic Ocean to the east.

With a territorial area of 114.773 Km^2, Garopaba has a population of 29,959 inhabitants and a population density of 261.03 inhabitants per square kilometer (Brazilian Institute of Geography and Statistics IBGE, 2022). The Municipal Human Development Index (MHDI) is 0.753, considered high by the United Nations Development Programme (UNDP).

The methodology of this study is divided into diagnosis of solid waste generated in the municipality of Garopaba, estimation and analysis of GHG emissions using the GHG Protocol tool, and the influence of greenhouse gases from composting on global warming, as described below.

2.1 Diagnosis of solid waste generated in the municipality of Garopaba

The diagnosis of solid waste generated in Garopaba was based on the analysis of data from official sources, including the Municipal Basic Sanitation Plan of Garopaba City Hall (PMSG), the State Solid Waste Plan of Santa Catarina (PERS/SC), and the National Sanitation Information System (SNIS).

This stage involved collecting information about origin, volume, and characteristics of urban solid waste, as well as the methods of disposal and final destination adopted in the municipality of Garopaba. The main objective was to analyze the gravimetric composition and quantities of collected waste, providing a comprehensive understanding, especially of organic waste generation.

The determination of the solid waste amount in each fraction requires the consideration of two essential variables:

a) Quantity collected over a period (day, month, or year): Ideally, the data should represent an annual average to avoid seasonal influences.

b) Gravimetric characterization of the municipality's waste: The analysis should include, at least, the differentiation between dry recyclables, refuse, and compostable organics.

To estimate the amount of organic waste generated in Garopaba, data on the total quantity of waste collected annually (from 2017 to 2021) was obtained from the document "Revision of the Municipal Basic Sanitation Plan: Product II – Technical-Participatory Diagnostic Report" by Garopaba City Hall. The information on collected waste in this document was provided by the company responsible for waste collection services in the municipality (Garopaba, 2023). For the year 2022, data from the SNIS was used.

The PERS/SC provides the gravimetric characterization of waste generated in Santa Catarina, grouped by solid waste integrated management region. This survey uses gravimetric data collected directly from municipalities, either through questionnaires or information available in municipal and/or intermunicipal solid waste plans (Santa Catarina, 2018).

Based on this data, the generation of each waste category in the municipality was calculated using Equation 1:

$$Q_{fraction} = P_{fraction} \, x \, Q_{total} \tag{1}$$

where:
Q_fraction = amount of waste generated from a given fraction (organic, recyclable, or refuse) in a given period (t/year);
P_fraction = percentage of the given fraction relative to the total collected waste (dimensionless);
Q_total = total amount of waste generated in a given period (t/year)

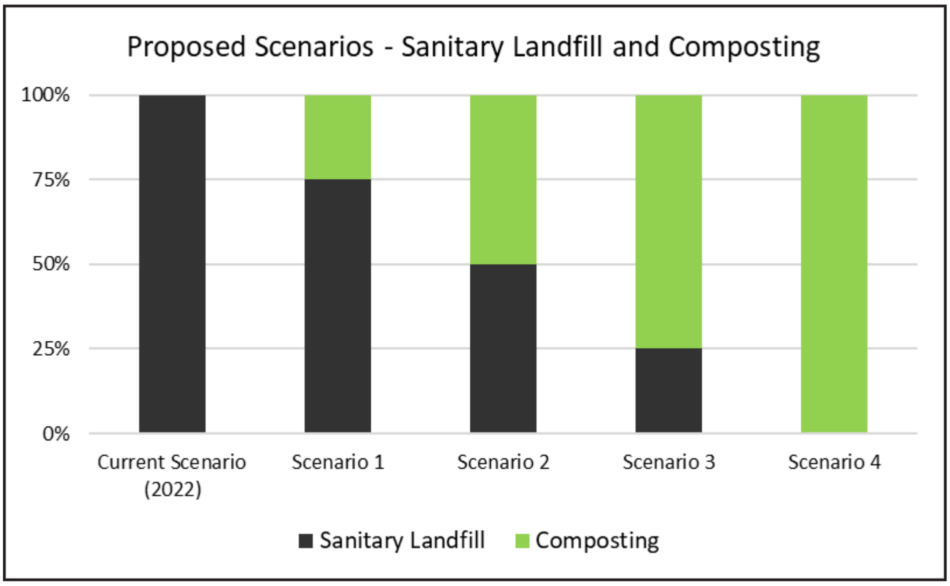
The amount of waste per fraction, especially the calculated organic fraction, was used as the basis for the analysis of the proposed scenarios in the GHG emissions quantification stage using the GHG Protocol tool. The organic fraction refers to Municipal Solid Waste (MSW) and includes food waste, garden and park waste, and other biodegradable materials commonly generated in households, restaurants, markets, and public spaces. These materials decompose naturally and are suitable for composting, making them a key focus in evaluating waste management strategies and their impact on GHG emissions.

2.2 Estimation and analysis of GHG emissions using the GHG Protocol tool

The amount of organic waste generated in the municipality of Garopaba in 2022 was considered in order to calculate and quantify GHG emissions using the GHG Protocol tool. These data were obtained during the solid waste diagnosis phase, based on information from the Municipal Basic Sanitation Plan of Garopaba City Hall (PMSG), the State Solid Waste Plan of Santa Catarina (PERS/SC), and the National Sanitation Information System (SNIS). The gravimetric composition presented in the PERS/SC is divided into recyclable waste, organic waste and refuse. Thus, it is assumed that the organic waste category corresponds to the fraction of waste which is suitable for composting.

To explore the potential climate benefits of composting as an alternative to landfilling organic waste, five scenarios were developed based on gradually increasing proportions of organic waste diverted to composting. The scenarios range from the current situation – where 100% of the organic waste is landfilled – to an idealized scenario in which 100% of this fraction is composted. The intermediate steps (75%, 50%, and 25% sent to landfill) were defined to simulate a progressive implementation trajectory, reflecting increasing investments in composting infrastructure and public engagement over time, as illustrated in Figure 3.

Figure 3 – Proposed scenarios for emission calculations using the GHG Protocol tool



Source: Authors (2024)

Table 1 presents the quantities of organic waste considered for landfill and composting in each scenario, the total represents the amount of organic waste generated in Garopaba (base year 2022):

Table 1 – Quantities of waste directed to landfill and composting in each of the proposed scenarios

	Current Scenario (2022)	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Waste quantity directed to landfill (t)	5,409.01	4,056.76	2,704.50	1,352.25	0.00
Waste quantity directed to composting (t)	0.00	1,352.25	2,704.50	4,056.76	5,409.01
Total (t)	5,409.01	5,409.01	5,409.01	5,409.01	5,409.01

Source: Authors (2024)

The Brazilian GHG Protocol Program tool (version 2024) was used to calculate and quantify the emissions related to organic waste directed to landfill and/or composting. This tool is compatible with ISO 14,064 standard and the calculation methodologies of the Intergovernmental Panel on Climate Change (IPCC).

The GHG Protocol methodology encompasses several stages for developing GHG inventories, considering Scopes 1, 2, and 3. For this study, the calculation of indirect emissions from solid waste treatment was selected, as indicated in Scope 3, using 2022 as the base year, which is the most recent data on the quantity of waste generated in the municipality of Garopaba.

In the “Landfilled Waste” section, in addition to the quantities of waste directed to landfill in each scenario, data were entered into waste composition table for the categories “C – Food Waste” and “E – Garden and Park Waste.” Since the PERS/SC does not separate food waste from garden and park waste, gravimetric composition data from the municipality of Florianópolis were used, due to its specific composition for these two categories. Combined, these categories present a composition similar to the organic waste in Garopaba, as shown in PERS/SC. By applying the rule of three, percentages of 68.38% for food waste and 31.62% for garden and park waste were obtained.

Moreover, more specific data regarding the landfill are necessary, such as the landfill classification and whether there is CH_4 recovery through flaring or use for electricity generation. In the case under study, the landfill is classified as category “A” – which includes waste management control, encompassing at least one of the following methods: (i) cover material; (ii) mechanical compaction; or (iii) waste leveling. This landfill also has CH_4 recovery through flaring without energy reuse.

For other data, such as biogas concentration (the fraction of CH_4 in the biogas) and the average methane recovery efficiency at the landfill, the cells were left blank, allowing the tool to use standard values set by the IPCC (2019).

In the “Composting” section of the tool, the quantity of waste directed to composting was entered in tons per year (t/year). Data as the emission factors for CH_4 and N_2O were left blank. Thus, the tool automatically uses the standard values provided by the IPCC (2019).

2.3 The influence of greenhouse gases from composting on global warming

The greenhouse gas (GHG) emission data quantified using the GHG Protocol tool, expressed in tCO_2e, were considered to evaluate the impact of reducing these emissions on global temperature variation. The methodological approach adopted follows the model proposed by Luiz (2022), which is based on the method developed by Ellis (2013).

Ellis' (2013) model considers variations in GHG emissions and their impact on global temperature rise. Equation 2, presented below, describes the relationship between temperature change and the concentration of CO_2 in the atmosphere, expressed in parts per million (ppm):

$$\Delta T = 1{,}66 \, ln\left(\frac{C}{C_0}\right) \tag{2}$$

Where:
ΔT = variation in global temperature (ºC);
C = final concentration of CO_2 (ppm);
C_0 = initial concentration of CO_2 (ppm);

This equation represents the temperature variation (ΔT) resulting from the change in CO_2 concentration (C_0 to C). The researchers emphasize that to calculate the temperature increase associated with changes in CO_2 concentration in the atmosphere, it is essential to consider the energy balance. An increase in CO_2 concentration makes the atmosphere less transparent to thermal radiation and reduces the amount of heat reflected into space by approximately 4 W/m^2. Applying this relationship to the equation, when CO_2 concentration is doubled ($C = 2\,C_0$), the estimated temperature increase is about 1.2 ºC (Ellis, 2013).

The results generated by the GHG Protocol are provided in tCO_2e, they were converted to ppm and inserted in Equation 2. Considering that 1 ppm of CO_2 is a volumetric measure, it was essential to work with moles during the calculations, converting into tons at the end. According to Trenberth and Smith (2005), the atmosphere mass is estimated at 5.1480 x 10^{18} kg. As the article shows, this value should be carefully estimated, as the commonly used method for calculating atmospheric mass, which involves multiplying sea-level pressure by the area of the Earth, may overestimate this mass by disregarding topography. The atmospheric composition results in a molar mass of 28.97 g/mol, which yields approximately 177.7 x 10^{18} moles in the atmosphere. Thus, 1 ppm corresponds to 177.7 x 10^{12} moles. Since 1 mole of CO_2 has a mass of 44.01 g, the mass corresponding to 1 ppm of CO_2 is 7.821 billion metric tons.

Since Ellis' (2013) model operates on a global scale, an extrapolation to a global scale was conducted considering the results of Garobapa's reduced emissions in the studied scenarios. This extrapolation considered the ratio between Garopaba's population and global population, allowing the determination of the potential impact of the analyzed scenarios in this study on a global scale. As Equation 2 is applicable to global temperature variation, the initial CO_2 concentration (C_0) considered (at the global level) was 415 ppm (IPCC, 2023).

3 RESULTS AND DISCUSSION

3.1 Diagnosis of solid waste generated in the municipality of Garopaba

The data obtained from the diagnosis of solid waste generated in Garopaba show variations in the generation and composition of waste over the years. Table 2 presents the quantity of recyclable, organic, and reject waste collected in the municipality from 2017 to 2022.

Between 2017 and 2022, the total amount of waste generated in Garopaba increased from 13,797.19 tons to 15,284.00 tons, representing a growth of approximately 10.8% over the analyzed period. The UNEP (2024) highlights that the increase in solid waste generation is a global trend, with 75% of this growth attributed to the increase in purchasing power and 25% to population growth, mainly driven by economic development.

Table 2 – Estimated quantity of waste by fraction in Garopaba – SC

Year	2017	2018	2019	2020	2021	2022
Quantity of recyclable waste (t)	6,019.71	6,104.13	6,411.96	6,899.71	6,713.56	6,668.41
Quantity of organic waste (t)	4,882.83	4,951.30	5,200.99	5,596.63	5,445.63	5,409.01
Quantity of reject waste (t)	2,894.65	2,935.24	3,083.27	3,317.81	3,228.29	3,206.58
Tota waste (t)	13,797.19	13,990.67	14,696.22	15,814.15	15,387.48	15,284.00

Source: Authors (2024)

The analysis of annual data reveals patterns and anomalies that may be important for the formulation of public policies and future strategies. For instance, the most significant increase in the total amount of waste in Garopaba occurred between 2019 and 2020, with a rise of 7.6%. This increase may be related to demographic changes caused by the COVID-19 pandemic or the growing purchasing power of the local population. Data from the Florianópolis waste meter, developed by Luiz (2022), was used for comparison purposes. Unlike Garopaba, the municipality of Florianópolis recorded an anomalous drop in waste collection between 2019 and 2020, with 6,601 tons less collected in 2020 compared to 2021.

In Garopaba, the quantity of recyclable waste initially presented a growth, reaching 6,899.71 tons in 2020. However, after 2020, there was a slight decline, reducing to 6,668.41 tons in 2022. Organic waste followed a consistent upward trend until 2020, rising from 4,882.83 tons in 2017 to 5,596.63 tons. After 2020, there was a slight decrease, reaching 5,409.01 tons in 2022. This behavior underscores the importance of implementing effective composting and organic waste management programs, as they represent a significant fraction of the waste generated. The quantity of reject waste also increased until 2020, rising from 2,894.65 tons in 2017 to 3,317.81 tons. After this peak, there was a small reduction, totaling 3,206.58 tons in 2022.

It is important to note that waste management practices, such as composting, remain negligible at the national scale. According to Brazilian Association of Waste and

Environment (ABREMA), based on data published by SNIS and Embrapa, approximately 300,000 tons of material were processed in composting facilities across Brazil in 2023, which accounts for only 0.4% of the total Municipal Solid Waste (MSW) generated in the country (Abrema, 2024).

Furthermore, there are significant regional disparities in access to basic waste management services, with southeastern regions of Brazil having more structured systems compared to the northern regions. Regionally, projections indicate that the South, Southeast, and Midwest regions surpass the national average in waste collection, with rates of 97.2%, 98.8%, and 95.2%, respectively. In contrast, the North and Northeast regions collect approximately 83% of the MSW generated, highlighting regional differences in solid waste management across the country (ABREMA, 2024). Considering these divergences, incorporating regional particularities is crucial when evaluating the potential scalability of waste management strategies beyond Garopaba.

According to the Waste Meter of Luiz (2022), Florianópolis experienced a significant increase in organic waste collection, rising from 2,843.00 tons in 2017 to 8,240.00 tons in 2022, representing a growth of 189.8%. This substantial increase can be attributed to the implementation of the Composting Law (Law Nº. 10.501, dated April 8th, 2019), which stablished the mandatory recycling of solid organic waste in the municipality of Florianópolis. This legislation, along with proper separation and disposal policies, reflects a significant change in the management of organic waste in Santa Catarina’s capital.

The annual variation in data suggests that waste collection and management in Garopaba are strongly influenced by seasonal factors, such as the population increase during the high tourist season. These data highlight the importance of considering seasonal fluctuations when planning and implementing waste management strategies and policies in the municipality. While approximately 800 tons of waste are collected monthly during the low season, this number rises to 1,500 tons per month during the peak season (Garopaba, 2023).

The presented data are essential for decision-making about solid waste management in Garopaba. The waste quantity and composition highlight the need to strengthen recycling programs, implement composting initiatives, and improve waste segregation. With the organic waste generation growth, the implementation of composting programs can significantly reduce the amount of waste sent to landfills, promoting a waste management approach focused on sustainability and circular economy.

To address the organic waste challenge, Garopaba should consider the establishment of a Municipal Solid Waste Management Plan (PMGRS), as recommended by the Brazilian National Solid Waste Policy (PNRS). This plan would enable the municipality to define clear strategies for reducing landfill disposal, promoting waste valorization, and integrating composting solutions into its waste management system. Additionally, investments in Waste-to-Energy (WtE) projects should be explored as a complementary strategy to reduce methane emissions from organic waste decomposition and generate renewable energy. The elimination of controlled dumps and improper dumping sites is another fundamental action that should be incorporated into Garopaba’s waste management strategy, ensuring compliance with national environmental regulations and improving urban sanitation.

Planning management strategies that consider seasonal variations can optimize resources and improve efficiency of waste collection and treatment. Collaboration between public authorities, the private sector, and local communities is essential to developing sustainable waste management solutions that address both short-term operational challenges and long-term environmental objectives.

This data contributes as a starting point for future analysis and public policy definition. Continuous monitoring and a more detailed analysis of the generated waste can enable dynamic adjustments to management strategies, promoting environmental sustainability and Garopaba’s community well-being. This diagnosis reinforces the importance of integrated planning and collaboration among public administration, the population, and private sectors involved in waste management.

3.2 Estimation and analysis of GHG emissions using the GHG Protocol tool

This section presents the analysis of the results obtained from comparing the amount of organic waste and GHG emissions across different proposed scenarios for organic waste management, using the GHG Protocol tool. Table 3 shows the key data used in the tool, demonstrating the amount of organic waste directed to landfills and composting, as well as the associated GHG emissions for each scenario.

Table 3 – Quantity of waste and GHG emissions in different scenarios

	Scenarios				
	Current (2022)	**1**	**2**	**3**	**4**
Quantity of organic waste directed to composting (t)	0.00	1,352.25	2,704.50	4,056.76	5,409.01
Quantity of organic waste directed to landfill (t)	5,409.01	4,056.76	2,704.50	1,352.25	0.00
Total (t)	5,409.01	5,409.01	5,409.01	5,409.01	5,409.01
GHG emissions from organic waste in composting (tCO_2e/year)	0.00	237.46	474.91	712.37	949.82
GHG emissions from organic waste in landfill (tCO_2e/year)	8,414.43	6,310.82	4,207.21	2,103.61	0.00
Total (tCO_2e/year)	8,414.43	6,548.27	4,682.12	2,815.97	949.82

Source: Authors (2024)

The scenarios were designed to assess the impact of the gradual replacing of organic waste disposal from landfills to composting. As shown in Table 3, the Current Scenario (2022) reflects the present situation where 100% of organic waste is directed to landfills. In subsequent scenarios (1 to 4), there is a progressive increase in the amount of waste directed to composting, where in Scenario 4, 100% of organic waste is composted. This change in waste management has significant implications for greenhouse gas emissions. Firmo et al. (2019) highlighted that recycling organic waste through composting offers a dual advantage: it diverts waste from landfills reducing the presence of biodegradable materials that produce methane under anaerobic conditions; and also promotes the recycling of organic wastes resulting in compost production, which causes additional benefits in GHG emissions reduction by the substitution of raw materials' extraction and processing, such as fertilizers.

In the current scenario (2022), it is observed that all organic waste generated is directed to landfills (5,409.01 tons). This scenario results in total GHG emissions of 8,414.43 tCO_2e/year. The high emissions stem from the anaerobic decomposition process of organic waste in landfills, which produces methane, a potent GHG. The literature consistently indicates that landfilling is the least attractive option regarding GHG emissions. Nordahl et al. (2020) reinforced this conclusion with their findings on GHG emissions, emphasizing that fugitive methane emissions are the main factor in the GHG footprint of organic waste. In any scenario where organics are deposited in landfills, it will result in higher GHG emissions.

By the implementation of Scenario 1, 1,352.25 tons of organic waste are directed to composting, while 4,056.76 tons continue to be directed to landfills. This scenario results in a significant reduction in total GHG emissions, which drops to 6,548.27 tCO_2e/year. The emissions from composting amount to 237.46 tCO_2e/year, while emissions from the landfill reduce to 6,310.82 tCO_2e/year. The decrease in total emissions reflects the reduction in the amount of waste directed to landfills and the lower impact of composting in terms of GHG emissions.

In Scenario 2, the quantity of composted waste increases to 2,704.50 tons, and consequently, waste directed to landfills decreases to 2,704.50 tons. Total GHG emissions in this scenario are reduced to 4,682.12 tCO_2e/year. Emissions from composting are 474.92 tCO_2e/year, and emissions from the landfill drop to 4,207.20 tCO_2e/year. The increasing allocation of waste to composting continues to contribute to the reduction of GHG emissions.

Scenario 3 proposes composting 4,056.76 tons of organic waste, leaving 1,352.25 tons to be directed to the landfill. Total GHG emissions in this scenario amount to 2,815.96 tCO_2e/year, with 712.38 tCO_2e/year from composting and 2,103.58 tCO_2e/year from the landfill. The reducing GHG emissions trend intensifies as composting becomes the organic waste managing main method.

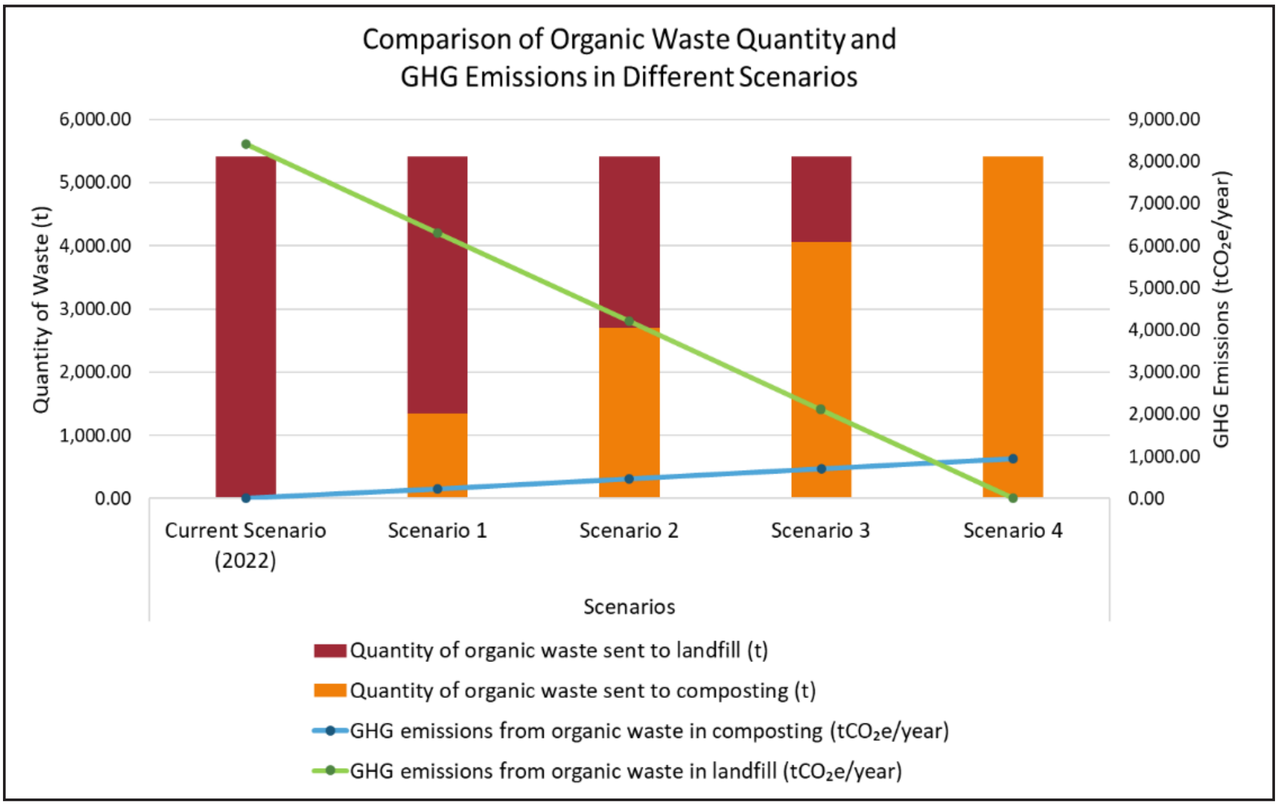
In Scenario 4, all generated organic waste (5,409.01 tons) is directed to composting, eliminating the waste disposal in landfills. This scenario results in the lowest total GHG emissions, totaling 949.82 tCO_2e/year, all coming from the composting process. There are no emissions associated with landfilling, as no waste is directed to this disposal method in this scenario.

The scenarios analysis emphasizes the importance of composting in reducing GHG emissions associated with organic waste. The transition from the current scenario (2022) to scenario 4 results in a reduction of approximately 88.7% in total GHG emissions. This significant decrease occurs because composting generates considerably fewer GHG emissions compared to landfilling. The findings are consistent with Santos (2020), who, despite using a different methodology — CDM AMS-III.F – Avoidance of Methane Emissions through Composting – Version 12.0, found a reduction of 83.5% in GHG emissions by diverting the same amount of organic waste from landfills to composting.

Various studies have demonstrated that composting emits significantly fewer GHGs than landfilling and incineration. Lou and Nair (2009) compared GHG emissions from organic waste composting and landfilling, concluding that landfilling results in higher GHG emissions compared to composting, that reflects the general consensus in the research community.

Figure 4 presents a comparison between different organic waste disposal scenarios and their respective greenhouse gas (GHG) emissions, based on the results obtained through the GHG Protocol tool. In the current scenario (2022), where all organic waste is sent to a landfill, the highest GHG emissions are observed, mainly due to methane generation under anaerobic conditions. As the scenarios progress, with a gradual increase in the fraction of waste diverted to composting, a significant reduction in total emissions is observed. This is because the composting process emits fewer GHGs per ton of waste treated compared to landfilling. Scenario 4, where all organic waste is directed to composting, exhibits the lowest GHG emissions among all the scenarios evaluated.

Figure 4 – Comparative chart of results obtained from the GHG Protocol tool



Source: Authors (2024)

The results presented demonstrate that the implementation of composting strategies can have a substantial impact on reducing greenhouse gas (GHG) emissions associated with organic waste management. The gradual transition through the proposed different scenarios offers a practical and incremental approach to implementing composting, yielding measurable results in terms of emission reduction. These findings highlight composting as a sustainable solution, evidencing its importance for the public policies determination focusing on urban solid waste management.

Firmo et al. (2019) stated that when evaluating waste policies from a cross-cutting perspective, their role is recognized not only in the context of climate change but also in pursuing global goals related to sanitation, affordable and clean energy, innovation and infrastructure, sustainable cities, and responsible production and consumption — all aligned with the Sustainable Development Goals (SDGs) defined by the United Nations (2015).

The results suggest that policies and practices encouraging the composting of organic waste can be effective in mitigating climate change. However, it is also essential to consider costs, necessary infrastructure, and public acceptance of these practices to ensure successful implementation. Transitioning to composting requires planning and investment, but the environmental benefits, especially in terms of GHG emission reductions, can be significant.

According to Luiz (2022), the alternative of treating organic waste through composting results in energy efficiency not only by considering the gases produced during the decomposition process but also because the application of the obtained organic compost improves soil quality, leading to less use of synthetic fertilizers, and it also reduces soil erosion and the use of herbicides.

Although this analysis focuses on gas emissions during the composting process itself, excluding truck transport and fuel combustion for equipment operation, the emission factors from composting are more significant in a broader context where each complete process of organic waste management can be compared. Mancini et al. (2022) applied a specific tool for composting to evaluate the carbon footprint of the process. The tool used by Mancini et al. (2022) is based on a life-cycle approach, aligned to international standards, including the GHG Protocol, IPCC guidelines, and the ISO 14040 series of standards.

In order to obtain composting's GHG emissions accounting, Mancini et al. (2022) considered various activities, encompassing the three scopes defined by the GHG Protocol: (i) energy and auxiliary material consumption; (ii) direct emissions of methane (CH_4) and nitrous oxide (N_2O) related to composting activities. Only atmospheric emissions of gases that potentially contribute directly to global warming, such as CH_4, N_2O, and CO_2, were considered. However, due to the biogenic nature of CO_2, which is considered neutral concerning global warming, this gas is not included in the accounting; (iii) emissions related to the treatment of waste generated from composting processes; and (iv) emissions resulting from the transport of inputs, products, and waste. The analysis encompassed both the direct use of energy, and the emissions associated with the materials transport, reflecting the complexity of the activities involved in the composting process.

3.3 The influence of greenhouse gases from composting on global warming

Based on the results obtained from the GHG Protocol scenarios, the calculations described in the methodology using the Ellis method (2013), Equation 2, were applied to estimate the contribution of the proposed scenarios to the variation in global temperature. To conduct this analysis, it was necessary to extrapolate the results to a global scale, considering the proportion of the world population in relation to the local population of Garopaba. This procedure was performed to estimate the influence of GHG emissions, assuming that the locally observed reductions would be globally applied.

The results, presented in Table 4, show the reductions in greenhouse gas (GHG) concentrations, expressed in parts per million (ppm), and the corresponding temperature variation (ΔT) for both Garopaba and on a global scale.

The results analysis shows that the studied scenarios indicate a progressive reduction in greenhouse gas (GHG) concentrations, ranging from 2.39E-07 to 9.54E-07 parts per million (ppm). Although these values may seem small, they represent the proportional decrease in emissions in each of the analyzed scenarios.

Table 4 – Reduction in GHG concentrations (ppm) in the atmosphere and temperature variation (ΔT) in Garopaba and globally

Scenarios	1	2	3	4
Emission Reduction (ppm)	2.39E-07	4.77E-07	7.16E-07	9.54E-07
ΔT (°C) Garopaba	-9.5E-10	-1.9E-09	-2.9E-09	-3.8E-09
ΔT (°C) Global	-0.00026	-0.00052	-0.00078	-0.00104

Source: Authorship (2026)

When examining the temperature variation (ΔT) for the municipality of Garopaba, it is noted that the estimated change is extremely small, ranging from -9.5E-10°C to -3.8E-09°C. When these results are extrapolated to a global scale, the temperature variation remains low, fluctuating between -0.00026°C and -0.00104°C, depending on the considered scenario.

These data reveal that although composting provides positive reductions in GHG emissions, its direct impact on mitigating global warming is quite limited when considered in isolation, especially on a local scale. The resulting temperature variations are minimal, both in Garopaba and globally. This suggests that while local composting practices contribute to emission reductions, they need to be part of a broader and coordinated effort to achieve a significant impact on global warming. Targeted public policies are essential to support the successful implementation and scaling of composting initiatives. Policies that promote composting infrastructure, offer financial incentives, and support public awareness campaigns can drive the adoption of composting practices and help achieve meaningful reductions in GHG emissions.

Beyond policy formulation, the feasibility of large-scale composting in Garopaba also depends on the availability of adequate infrastructure. It is necessary to further assess whether the municipality currently has the facilities and logistics required to support the expansion of composting activities. This includes identifying potential needs for investments in dedicated composting sites, equipment for processing organic material, and efficient systems for the collection of organic waste and the distribution of compost. Strengthening this infrastructure is essential for the successful implementation of composting as a sustainable municipal waste management strategy.

Luiz (2022) applied the Ellis (2013) methodology to analyze the greenhouse gas emissions from urban solid waste in Florianópolis, proposing waste recovery scenarios and estimating a global temperature reduction of approximately 0.94°C over 100 years. However, Luiz (2022) considered the total waste stream, not limited to organic waste and composting. This supports the idea that waste management needs to integrate a broader, coordinated effort to generate a significant impact on global warming.

According to Raju (2020), the global implementation of composting could reduce GHG emissions by 2.3 billion tons over the next 30 years. Reducing food waste is one of the most important actions to reverse global warming.

Various studies address the reduction of GHG emissions in the context of composting, which can enhance its contribution to mitigating global warming. Walling et al. (2020) discussed mathematical modeling to predict and optimize the composting process, while Yin et al. (2021) explored the use of biochar as an efficient strategy to reduce emissions during the process. Additionally, Sandelowsky (2021) proposed integrating composting into carbon capture programs to maximize its effectiveness. Saini and Bhatt (2020) discussed various sustainable agricultural strategies, highlighting composting as a viable solution to mitigate GHG emissions in the agricultural sector.

These studies converge on the importance of adjusting operational parameters to optimize composting and other agricultural practices, with the aim of minimizing greenhouse gas emissions. While Walling et al. (2020) and Yin et al. (2021) focused on the technical aspects and process modeling, Sandelowsky (2021) and Saini and Bhatt (2020) addressed practical implementation strategies and the economic and environmental benefits of these practices.

In summary, GHG emissions from composting, when mitigated, have a very small effect on temperature reduction, both locally and globally. However, it is crucial to recognize that each small contribution is valuable in the context of global mitigation efforts. This reinforces the importance of integrated and coordinated actions so that GHG reductions on a global scale reach significant levels, capable of influencing climate change in a more noticeable way, and consequently, global warming. Furthermore, effective urban solid waste management is closely linked to the Sustainable Development Goals (SDGs), encompassing issues of global social and environmental justice. The implementation of inclusive waste management policies and the promotion of practices such as composting can contribute to various SDGs, such as eradicating poverty, food security, public health, and combating climate change, as evidenced by the United Nations Environment Programme (UNEP, 2024).

There is a significant interrelationship between waste management, environmental pollution, global warming, and climate change. The processing and reuse of waste, including composting and the production of organic compost to be used in agriculture, are examples of practices that not only mitigate these problems but can also generate essential wealth and jobs, especially for developing countries (Raju, 2020).

4 CONCLUSIONS

This article analyzed the impact of greenhouse gas (GHG) emissions from composting on global warming, with a specific focus on the municipality of Garopaba. The study aimed to quantify and analyze the GHG emissions associated with composting and assess its contribution to global warming. Alternative scenarios for managing organic solid waste were proposed to increase the amount of waste directed to composting in the municipality.

The results indicated that composting, compared to landfilling, significantly reduces GHG emissions, corroborating existing literature. The transition from the Current Scenario (2022), in which all organic waste generated is directed to landfills, to Scenario 4, in which all organic waste generated is directed to composting, results in a reduction of approximately 88.7% in total GHG emissions.

Regarding the contributions of composting to global warming, the results are positive, albeit modest. Although composting offers significant reductions in GHG emissions, its direct impact on mitigating global warming is limited when considered in isolation, especially on a local scale. The resulting temperature variations are minimal, both in Garopaba and globally. This suggests that while local composting practices contribute to emission reductions, they need to be part of a broader and coordinated effort to achieve a significant impact on combating global warming. Targeted public policies are essential to support the successful implementation and scaling of composting initiatives.

In addition to the environmental benefits associated with GHG emissions reduction, the implementation of composting programs can also generate significant social and economic impacts. Composting has the potential to create local jobs across the entire organic waste management chain – from source separation and collection to processing and compost distribution – thus promoting decent work opportunities and social inclusion, especially in vulnerable communities. These co-benefits strengthen the role of composting as a sustainable development strategy and contribute directly to several Sustainable Development Goals (SDGs), such as SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). As such, promoting composting practices not only supports environmental policies but also acts as a driver of social equity and local economic development.

It is important to highlight that this study focused on estimating the contribution of composting to temperature reduction and global warming. However, this estimation was based on specific data from the municipality of Garopaba, where the fraction of organic waste accounts for approximately 35% of the total waste generated. This percentage is lower than the averages for both Brazil and globally, where organic waste typically constitutes around 50% of the total waste generated. This difference may influence the results, and therefore, it is necessary to consider that the conclusions of this study may vary in contexts where the proportion of organic waste is higher. Future studies could explore these variations to assess the impact of composting in different regional and global contexts.

The methodology applied in this study can be replicated in other municipalities in Brazil. The approach for diagnosing solid waste generation, estimating GHG emissions using the GHG Protocol tool, and analyzing the climate impact of different waste management scenarios can serve as a model for small cities that lack data on GHG emissions from the waste sector. To implement this methodology in other municipalities, access to local waste data is essential. For the successful implementation of municipal composting, integrating this practice into municipal waste management plans, promoting environmental education, and engaging local stakeholders to support composting initiatives are crucial.

For larger urban centers, adaptations are necessary due to the higher volume of waste generation and the complexity of municipal waste management. The methodology would need to be applied at a regional or district level. In these cases, decentralized composting solutions and integrated waste treatment systems are recommended. Furthermore, technological advancements, such as real-time waste monitoring, could enhance the efficiency of waste collection and treatment. The implementation of regulatory policies, financial incentives for composting, and public-private partnerships would be key to scaling up this approach in large cities, ensuring effective waste management and significant GHG emissions reductions.

Public policies to promote composting and proper waste management should focus on economic incentives, infrastructure development, and public engagement. Financial support through tax benefits and subsidies can encourage composting initiatives and the adoption of organic waste treatment technologies. Investments in infrastructure, such as composting facilities and decentralized collection systems, are essential to enhance efficiency. Educational campaigns and community engagement programs can raise awareness about waste separation and the environmental benefits of composting. Additionally, establishing partnerships between municipalities, private companies, and local cooperatives can streamline waste management processes. Implementing regulatory frameworks and monitoring mechanisms is also crucial to ensure compliance with environmental standards and track progress in reducing greenhouse gas emissions.

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Authorship contributions

1 – Glenda Fauth

Specialization in Sustainable Projects, Climate Change, and the Carbon Market from the Federal University of Paraná
https://orcid.org/0009-0000-2666-8808 • glendafauth@gmail.com
Contribution: Conceptualization, Investigation, Methodology, Writing - original draft

2 – Cássio Aurélio Suski

PhD in Science and Materials Engineering from Universidade Federal de Santa Catarina
https://orcid.org/0000-0002-3965-4373 • cassio.suski@ifsc.edu.br
Contribution: Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing

3 – Juliano da Cunha Gomes

PhD in Environmental Engineering from the Federal University of Santa Catarina
https://orcid.org/0000-0003-0312-4933 • juliano.gomes@ifsc.edu.br
Contribution: Supervision

4 – Débora Souza Alvim

PhD in Sciences from the Institute of Energy and Nuclear Research
https://orcid.org/0000-0003-1501-4563 • deborasalvim@gmail.com
Contribution: Funding acquisition, Resources, Supervision, Validation, Visualization

5 – Pedro Fernando Wengrzyn dos Passos

Electrical Engineering student at the Federal Institute of Santa Catarina
https://orcid.org/0009-0005-4642-8285 • pedrofernandopassos@gmail.com
Contribution: Data curation

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