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**Comparative analysis between the impacts produced by centralized
biowaste management – a hospitality sector case study in Brazil**

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ABSTRACT

This article aims to evaluate the environmental impacts of different centralized biowaste management scenarios from the hospitality sector of the tourist city of João Pessoa, Brazil. To this end, a life cycle assessment was carried out, comparing different scenarios for the centralized treatment of biowaste based on territorial characteristics. The life cycle inventory was built using the Ecoinvent 3.0.1 database and Simapro software. The environmental impacts were assessed using the CML method, considering eight categories of impacts, such as global warming by greenhouse gases (GHG) and ozone layer depletion. The results show that the disposal of biowaste in João Pessoa's landfill (current management scenario) has significant environmental impacts when compared to diverting this waste to composting or anaerobic digestion, for example, in the global warming category, where the net impact of the landfill is 1.045 kg CO₂ eq, while that of composting and anaerobic digestion is 0.18 and 0.17 kg CO₂ eq, respectively. Furthermore, the comparison between centralized composting and anaerobic digestion indicates that composting is the scenario that produces the least negative environmental impacts for 62% of the categories analyzed. Therefore, this article points out that the current management of biowaste from the hotel sector in João Pessoa has several negative environmental impacts, making it necessary to implement actions that promote diverting biowaste flow from the landfill to other centralized treatment systems. It should be noted that an interdisciplinary analysis is needed to assess the social and economic aspects of the best option for treating and recovering organic waste.

Keywords: Biowaste, Life Cycle Assessment, Composting, Anaerobic Digestion, Centralized biowaste management, Hospitality sector

1. INTRODUCTION

Biowaste represents a large part of the municipal solid waste (MSW) produced worldwide, accounting for more than 50% of the MSW generated in various regions [29, 42]. According to the Brazilian National Solid Waste Plan, the US Environmental Protection Agency (EPA), and the French Ecological Transition Agency (ADEME), biowaste is produced by a variety of sources, including residential, industrial, commercial, retail, hospitality, and institutional sectors [3, 5, 11]. They identify the agri-food industry, restaurants, bars, hotels, open-air markets, supermarkets, and the maintenance of green spaces as the higher contributors to biowaste production [4, 52].

The hospitality sector can be a significant source of biowaste production [4, 52]. In this sense, the latest official figures from the Brazilian government indicate that in 2016, the country had 31,000 hotels, which offered approximately one million housing units and two million beds [10]. The hospitality sector in João Pessoa is made up of 72 lodging establishments, which offer approximately 4,000 housing units and 9,000 beds [10]. Organic waste generation in João Pessoa's accommodation establishments is estimated to be 900 tons per year, which is finally disposed of in the city's landfill without any material or energy recovery [28, 42]. The disposal of biowaste in dumps or landfills leads to various social, environmental, and economic impacts, mainly from the emission of methane gas (CH₄), contamination of groundwater by leachate, and effects on human well-being and health [21, 36, 37] in addition to the reduction in the quality of recyclable waste [42].

According to Pirani and Arafat [41], the large generation of MSW and its inadequate disposal is one of the higher environmental impacts caused by the hospitality sector. The literature review recently carried out by Quaresma and Athayde Júnior [44] indicates that the production of solid waste in the hotel sector worldwide is generally between 0.32 kg.guest⁻¹.day⁻¹ and 6.57 kg.guest⁻¹.day⁻¹, and can vary according to various characteristics, such as the number of guests, the number of beds and rooms, the services offered, such as the different types of meals provided, and the existence of green areas [1, 40].

In terms of composition, biowaste makes up the bulk of the waste generated by hotel establishments, accounting for more than 50% of total solid waste production [24, 40, 44, 50]. According to Quaresma et al. [45], in a study carried out in a hotel in João Pessoa, food waste, such as leftovers, made up approximately 54% of the organic waste generated in lodging establishments. However, a significant portion of this waste comprises fresh coconuts, a generation characteristic of the coastal region of northeastern Brazil.

In Brazil, municipalities manage solid waste in urban areas, from collection to final treatment. However, depending on their characteristics, such as volume and hazardousness, waste generated by economic activities can be classified as MSW [12]. Nevertheless, there is no data collection system in Brazil to identify the major generators of solid waste. In this context, such waste is usually collected with the other MSW to be disposed of in landfills, affecting the MSW management system in tourist areas. For example, Chaabane et al. [13] show that hotels in the city of Hammamet

(Tunisia) produced 46% of the total MSW generated in the municipality and that 83% of hotels send their waste to the landfill.

Therefore, it is essential to progress toward implementing source separation of biowaste to recover it and reduce its disposal in landfills. An extended literature exists that compares centralized composting (CC) or anaerobic digestion (AD) with landfilling, most frequently using Life Cycle Assessment (LCA), to help decision-makers find the most environmentally friendly options. LCA is an environmental assessment method that connects waste flows to potential environmental impacts, thus helping analyze and compare different management scenarios and supporting government organizations in planning actions [8, 14, 47]. In addition to choosing the technology, it is essential to consider territorial aspects [51], such as the transport route and treatment and recovery areas.

Thus, several authors have used LCA to estimate the specific impact of biowaste management scenarios for different impact categories [19, 20, 22, 47]. Rotthong et al. [47] and Ademe [2] show that treating biowaste by centralized composting is more impactful than centralized anaerobic digestion regarding global warming, ozone depletion, eutrophication, and consumption of mineral resources. On the other hand, De Boni et al. [19] point out that GHG emissions from a centralized composting plant are lower than those from a landfill. Also, Weidner et al. [53] point out that through biowaste's energy and material recovery, anaerobic digestion can reduce GHG emissions by 105% compared to landfill. At the same time, this reduction is 76% for centralized composting. Guillaume et al. [22] show that due to energy recovery, anaerobic digestion has higher benefits compared to centralized composting.

However, despite the vast literature available, there still needs to be more data and studies on the environmental impact of biowaste management systems from large producers and, more specifically, from the hospitality sector. This problem of data availability is even more severe for countries in the south hemisphere, such as Brazil, which are at the beginning of implementing new strategies based on the recovery of energy and materials, as analyzed by [23, 38, 48] who addressed the recovery of household or municipal solid waste in Brazil.

The subject of this article is the hotel sector in João Pessoa, a coastal city located in the north-east of Brazil, which has tourism as a fundamental part of its economic development. Given the above, the main objective of this article is to analyze different scenarios for managing organic waste from the hotel sector in João Pessoa.

In this sense, this article aims to add to the literature on the life cycle assessment of urban solid waste management in Brazilian cities, which is still in the consolidation phase. In addition, the research emphasizes the importance of regionalizing data sets to build a life cycle inventory adapted to the Brazilian context.

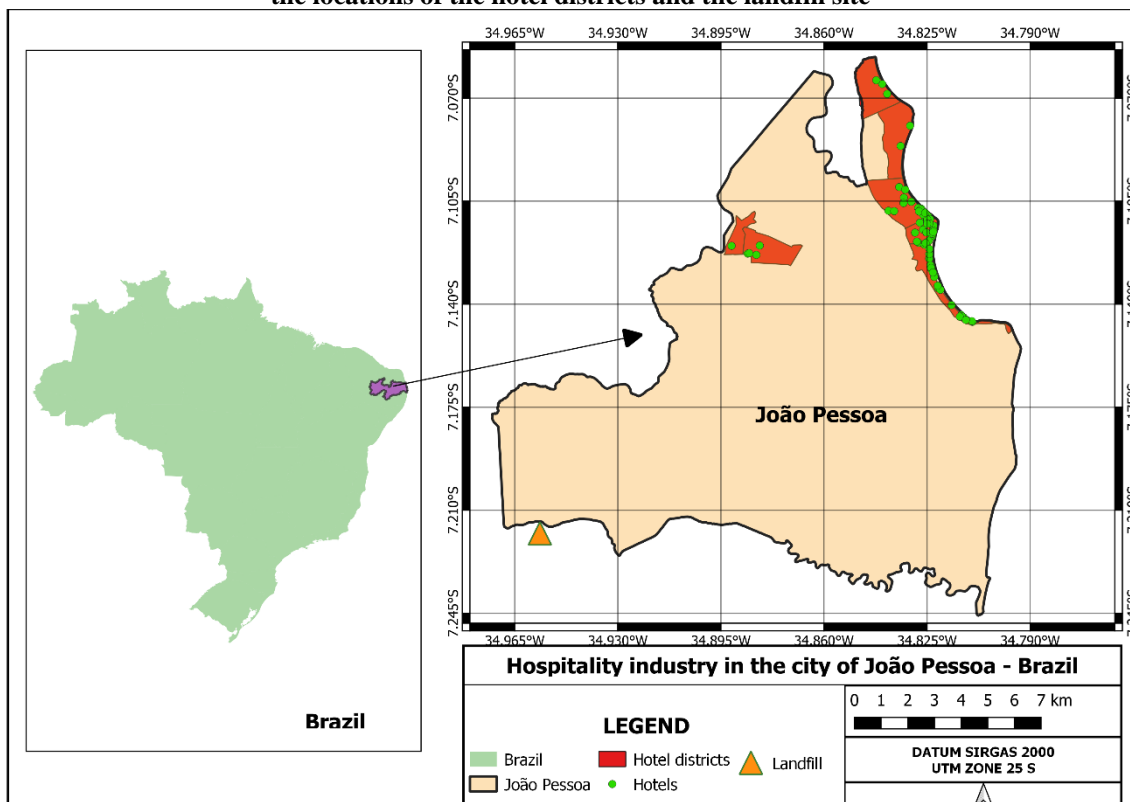
After the introduction, the article is divided into methodological aspects, which highlight the management of organic waste in João Pessoa and the considerations applied to the development of the life cycle analysis, such as the description of the scenarios, construction of the inventory, impact, and sensitivity analysis. The results and discussion will compare and assess different treatment scenarios in terms of evaluating life cycle impacts and sensitivity analysis.

2. MATERIALS AND METHOD

2.1 Biowaste management system for the hospitality sector in João Pessoa

This research was developed in João Pessoa, the capital of Paraíba state, located in the coastal region of northeastern Brazil (Figure 1). João Pessoa has a coastline approximately 24 km long, divided into nine beaches. Its coastline is the city's main tourist attraction.

Fig. 1 Representation of the city of João Pessoa in the region of Paraíba, Brazil, indicating the locations of the hotel districts and the landfill site



The management of MSW in João Pessoa is the municipality's responsibility, which provides the services of urban cleaning, solid waste collection, transportation, and final disposal [28]. If the waste produced by economic agents, such as the hotel sector, is not hazardous, and its volume is less than 200 l.day⁻¹, its collection and treatment are the municipality's responsibility, and it is characterized as urban solid waste [12]. However, there is currently no distinction between household solid waste and waste from economic activities and, as a result, both are mixed and disposed of in the city's landfill, without there being any material or energy recovery of the solid waste, reflecting the reality of most Brazilian cities [11, 28].

The latest available data showed that, set out in the public document entitled João Pessoa Municipal Solid Waste Management Plan, shows that João Pessoa produced an estimated 263,000 tons of household solid waste in 2013, at a rate of 0.94 kilograms per inhabitant per day [28]. Of this waste, 35% was food waste, and 16% was green waste [28].

According to data obtained in July 2022 from the Brazilian Ministry of Tourism, the city's hospitality sector comprises 72 lodging establishments, 93% of which are located in the coastal zone of the city (Figure 1), a place with the highest tourist activity [10].

The generation of solid waste from the hotel sector in João Pessoa was analyzed in previous research and was estimated at 1514 tons per year [43]. On average, this waste consists of organic waste (57%), mostly food waste, recyclable dry waste (24%), and non-recyclable waste (19%) [43]. Thus, the generation of organic waste from the hotel sector in João Pessoa is estimated at 870 tons per year. This waste is disposed of in the landfill in João Pessoa, without any segregation in the source of generation and energy or material recovery [43].

2.2 Life Cycle Assessment (LCA)

The LCA follows the methodology proposed by ISO 14040 [6], covering the objective, inventory, impact assessment, and interpretation of results, as suggested by the regulation. Thus, this LCA aims to assess the environmental impacts of different scenarios of centralized biowaste management. Centralized systems are those in which waste is collected from producers and transported to a treatment plant. The functional unit is the treatment of 1 kg of treated biowaste, as suggested by [2].

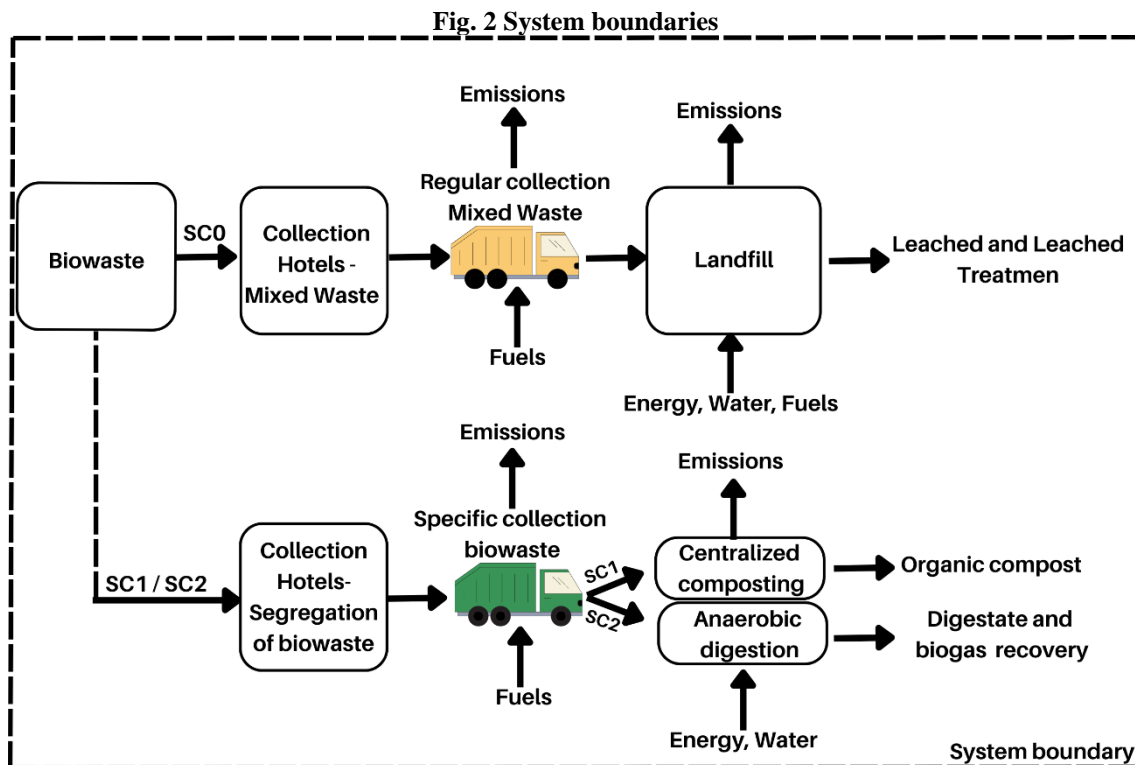


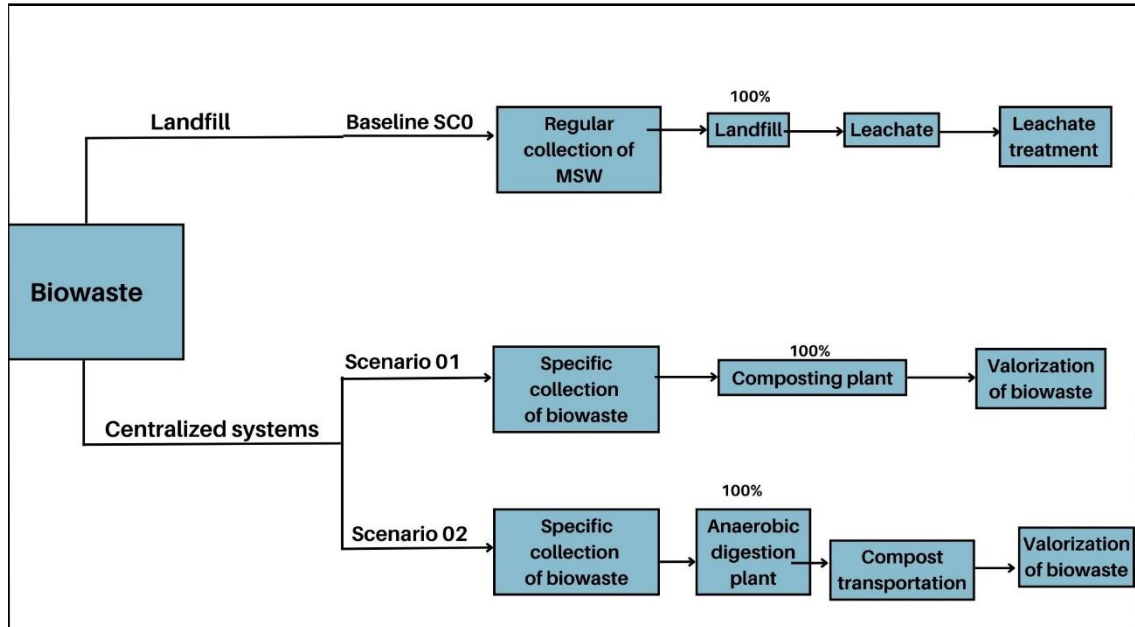
Figure 2 illustrates the boundaries of the system under consideration. The system's boundary meets the assumption from gate to grave, analyzing a specific part of the life cycle, as explained in NBR 14040 [6]. In other words, aspects from waste collection to final disposal or recovery were considered. Infrastructure, energy, water, and fuel consumption data were considered inputs. As output data, GHG emissions, the treatment of leachate from the landfill (SC0), organic compost (SC1), and digestate and biogas (SC2) were considered.

2.2.1 Scenario description

In Scenario SC0 (Baseline), 100% of biowaste from the hospitality sector is collected through the city's regular MSW collection, with no separation between organic, dry, recyclable, and non-recyclable. This scenario reflects the current situation of biowaste management in João Pessoa. The system for recovering the biogas generated at the landfill is still being implemented, and there is not enough data to draw any conclusions. Regarding the recovery of recyclable waste, the city of João Pessoa does not have a consolidated selective collection program, and there is no data available on the volume of waste recovered at the landfill. It was, therefore, assumed that MSW is

collected and disposed of in the landfill without any energy or material recovery. Figure 3 illustrates the scenarios evaluated in this investigation.

Fig. 3 Description of the scenarios evaluated



Scenario SC1 considers centralized composting as an environmentally appropriate method for biowaste management [12]. Thus, 100% of biowaste from the hospitality sector is separated at source and collected through a specific organic collection. After being collected, the waste is transported to a centralized composting unit, where it is materially recovered through the production of organic compost. According to Soares et al. [49], organic compost can be applied to the soil to improve its physical, chemical, and biological properties and provide nutrients for plants. This way, organic compost was considered a substitute for conventional chemical fertilizers.

In scenario SC2, 100% of the biowaste is separated at the source of generation, collected, and sent to an anaerobic digestion plant. For this scenario, the material and energy recovery of organic waste was considered since, during anaerobic digestion, the conversion of organic matter into biogas and the production of digestate occur, which are one of the most significant benefits of this technology [2, 5, 27]. Therefore, in this scenario, organic waste is valued through the use of digestate as an organic fertilizer, replacing conventional fertilizers, and biogas for energy production.

These scenarios were considered to be suited to Brazilian reality. However, other scenarios could be analyzed, such as incineration and decentralized treatment.

2.2.2 Life cycle inventory

The life cycle inventory was created according to the Ecoinvent 3.0.1 database, using the Software SimaPro 8.4. The Ecoinvent data was supplemented with data from the literature and primary local data collected from a territorial analysis of João Pessoa, through the geographic information system, using QGIS software. The territorial analysis included establishing a transportation route for organic waste to treatment systems and identifying suitable areas for the recovery of this waste.

Furthermore, for the SC0 scenario (baseline), adaptations were made to adapt the landfill modeled by Ecoinvent to the Brazilian context, as discussed in section 2.2.2.1, using the literature corresponding to the LCA of landfills located in Brazil, as Silva et al. [48]; Ibáñez-Forés et al. [26]; Paes et al. [38]. Table 1 illustrates the data used to construct the GHG emissions inventory. Table 1 illustrates the data used to build the GHG emissions inventory. Figure 4 illustrates the systems taken into account when drawing up the Life Cycle Inventory (LCI).

Fig. 4 Centralized biowaste management system in João Pessoa, Brazil

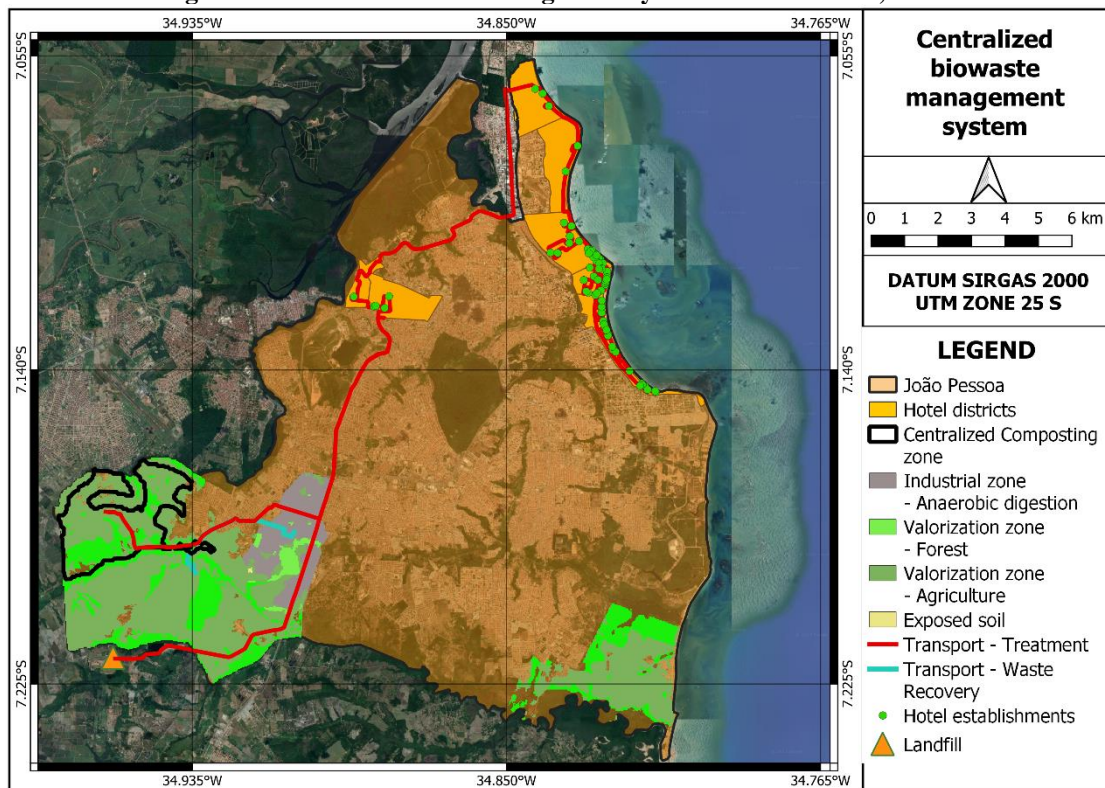


Table 1 Life cycle inventory concerning 1 kg functional unit

Emissions (kg)	Landfill	Central composting	Anaerobic digestion	Source
Methane	3.5E-2 (b)	2.20E-5 (a)	3.80E-5 (a)	(a) [2] (b) [23]
Volatile Organic	0	4.90E-5 (a)	0 (a)	(a) [2]
Carbon dioxide	1.55E-2 (b; c; d)	1.10E-1 (a)	8.10E-3 (a)	(a) [2]; (b) [48] (c) [38]; (d) [34]
Ammonia	2.27E-4 (b)	6.90E-7 (a)	1.28E-4 (a)	(a) [2]; (b) [34]
Carbon Monoxide	4.09E-5 (b)	0 (a)	2.0E-6 (b)	(a) [2] (b) [23]
Sulfur Oxide	1.70E-4 (a;b)	0	0	(a) [23]; (b) [34]
NoX - atmosphere	4.17E-5 (a; b)	0	0	(a) [23] ; (b) 38
Nitrous oxide	6.9E-4 (a)	0	0	(a) [48]
Nitrate - water	0	6.1E-3 (a)	0	(a) [2]
Methane - water	1.37E-5	0	0	(a) [23]
COD – water	3.82E-5	0	0	(a) [23]
BOD – water	9.12E-5	0	0	(a) [23]
Ammonia – water	2.02E-5	0	0	(a) [23]
Organic Nitrogen - water	1.50E-6	0	0	(a) [23])
Phosphorus – water	6.19E-7	0	0	(a) [23]
Nitrogen Total – water	9.12E-8	0	0	(a) [34]

The end-of-life modeling follows the substitution approach. The recovery of biowaste was included in the inventory as a positive impact, with the avoided production of fertilizers being considered material recovery and the avoided production of energy being considered energy recovery.

2.2.2.1 Regionalized landfill

The "Municipal solid waste treatment of sanitary landfill" procedure from the Ecoinvent 3.0.1 database served as the basis for creating the landfill's Life Cycle Inventory. However, this modeling represents Swiss conditions, where MSW contains 22% biowaste, in contrast to Brazilian landfills, where MSW consists of, on average, 45% biowaste, potentially leading to higher impacts [11; 18]. (See Online Resource).

In addition, while the Ecoinvent landfill database accounts for the burning of sludge from leachate treatment, such a practice does not occur at the João Pessoa landfill and was therefore not included in this research. To regionalize Ecoinvent's landfill database and better represent a Brazilian landfill, authors such as Ibáñez-Forés et al. [26], Silva et al. [48], Paes et al.[38], Gutierrez et al. [23] and Lima et al. [32] were used as resource data to complement, mainly with data on GHG emissions, energy, and water consumption (See Online Resource). Finally, a set of facultative lagoons was added to treat the leachate generated in the landfill, bringing it closer to the reality in João Pessoa [28].

Using the QGIS software and the method established for estimating regular solid waste collection routes in João Pessoa [28], the route for the regular transportation of

MSW from the neighborhoods belonging to João Pessoa's hospitality sector was dimensioned, corresponding to a distance of 234.88 km. However, it is estimated that the production of hotel solid waste corresponds to approximately 4% of the total generation of MSW from hotel districts [43]. Therefore, to specifically analyze the impact of transporting hotel solid waste to the landfill and compare the regular collection of MSW with the specific collection of organic waste, considering the distance of the route adopted corresponds to 4% of the total distance and is estimated at 9.4 km.

The literature and the Ecoinvent database provided the energy and water consumption values for the landfill's operation, as shown in Table 1. The output data considered is related to GHG emissions (Table 1), taking into account data from the literature by authors who have made estimates of GHG emissions or measurements in Brazilian landfills (See Online Resource) [18, 23, 26; 34, 38, 39, 48].

2.2.2.2 Centralized Composting

The "Biowaste treatment, composting" procedure from the Ecoinvent 3.0.1 database served to compile the centralized composting inventory. The infrastructure modeled by the Ecoinvent database considers the centralized composting in an open plant with a capacity to treat 10,000 t.year⁻¹ of biowaste and a useful life of 25 years, including activities of reception, weighing, crushing, and storage of the raw material, digestion, aeration and conditioning of the compost [18]. In addition to the infrastructure, electricity consumption equivalent to 0.047 kWh.kg⁻¹ treated biowaste and water consumption of 0.426 l.kg⁻¹ [33] were considered input data.

This scenario considers the segregation of biowaste at the source of generation (hospitality sector) and its transport to a centralized composting plant. As there is no centralized composting plant in João Pessoa, this area was selected by Belli [7] as suitable for setting up a biowaste treatment plant. The author considered territorial, environmental, and geographical criteria when choosing the area and the capacity for local recovery of the biowaste treated there. According to Belli [7], this area is located in the south of João Pessoa and consists of 5.29 km² of agriculture and 1.83 km² of forest remnants (Figure 4).

Thus, using QGIS software tools, an estimated collection route of 60.43 km was plotted between João Pessoa's hospitality sector and the centralized composting installation area. In addition, the study considered the local recovery of biowaste in the

forest and agricultural remnant areas within the treatment area itself. Finally, the biowaste produced in the hospitality sector is mainly food waste. Therefore, green waste from forest remnants and agricultural areas was considered structuring materials for centralized composting.

2.2.2.3 Anaerobic Digestion (AD)

The "Biowaste treatment of organic waste by anaerobic digestion" process from the Ecoinvent 3.0.1 database served to compile the AD inventory. The infrastructure of this process considers the activities of storage, weighing, and crushing of waste, pre-treatment, digestion, and solid/liquid separation, with the capacity to treat 10,000 t.year⁻¹ of biowaste and a useful life of 25 years [18]. The investigation used data from Ecoinvent 3.0.1 for electricity and thermal energy consumption but did not consider water consumption [18].

To recover energy from biowaste the study considered the industrial district of João Pessoa a suitable location for an anaerobic digestion plant. Using QGIS software tools, a transportation route of 51.32 km was estimated for biowaste from the hospitality sector. In addition, a route of 2.64 km was estimated for transporting the digestate, which is to be used as fertilizer in the region considered for the centralized composting plant (Figure 4).

GHG atmospheric emissions and positive impacts were considered as output data [2]. The indirect positive impacts were the detour of biowaste transport to the landfill, and the direct benefits were the use of digestate through the avoided production of chemical fertilizers, the recovery of biogas, and the avoided production of electrical and thermal energy from other generation sources. For the avoided production of thermal energy, a production of 0.235 kWh was considered, of which 0.17 kWh was valorized through its use in other sources and 0.064 kWh reused in the plant itself [2, 3].

2.2.3 Life Cycle Impact Assessment

Among the studies that use LCA as a decision-support tool for analyzing solid waste management, the impact assessment methods constantly used are CML and ReCiPe, with CML being identified in studies carried out in Lappeenranta, Finland [25], João Pessoa, Brazil [26]; Italy [8,19], Brasília, Brazil [48], Sorocaba, Brazil [39], São Paulo, Brazil [31], Rio de Janeiro, Brazil [16], and Barcelona, Spain [33]. Thus,

there is a predominance in the choice of the CML method for studies carried out in Brazil.

Thus, the life cycle impact assessment (LCIA) was carried out using the CML-IA baseline method, as recommended in the literature [8, 19, 25, 26]. The impact categories provided by the CML method, Global Warming, Acidification, Eutrophication, photo-oxidant formation, Human toxicity, Fossil fuels, Minerals resources, and Ozone layer depletion were analyzed (Table 2). These categories were selected as they are the most cited as relevant to solid waste management studies, such as [20; 22; 47].

Table 2 Impact categories used in life cycle impact assessment

Categories	Units	Description
Global Warming	kg CO ₂ eq	Related to greenhouse gas emissions
Acidification	kg SO ₂ eq	Emissions of nitric acid, sulfuric acid, phosphoric acid, nitric oxide, ammonia, etc.
Eutrophication	kg PO ₄ eq	Associated with excessive levels of macronutrients in the environment caused by emissions of ammonia, nitrates, nitrogen oxides and phosphorus into the air or water
Formation of photo-oxidants	kg C ₂ H ₄ eq	Formation of reactive substances harmful to human health and ecosystems, depending on the amounts of carbon monoxide, sulfur dioxide, nitrogen oxide, volatile organic compounds of ammonium and non-methane
Human toxicity	kg 1,4-DB eq	Effects of toxic substances on the human environment
Consumption of mineral resources	kg Sb eq	Related to mineral extraction
Consumption of fossil fuels	MJ	Use of fossil fuels
Ozone depletion	kg CFC-11 eq	Defines the potential for ozone depletion from the emission of different gases

Source: [18]

The LCIA was analyzed using net impacts, which refer to the difference between the impacts produced and avoided (Equation 01) in each impact category (i). The impacts produced correspond to GHG emissions, treatment center infrastructure, energy consumption, and transportation (see Online Resource 3). Positive impacts refer to avoided energy production (SC2) and avoided fertilizer production (SC1 and SC2) (See Online Resource).

$$Net\ impacts_i = impacts\ produced_i - impacts\ avoided_i \quad (Eq. 01)$$

2.2.4 Sensitivity Analysis

Sensitivity analysis aims to ensure the reliability of the analyzed system by identifying the parameters that most significantly influence the results obtained. In this

sense, scenario analysis was adopted, following the methodology proposed by Clavreul et al. [15], which tests various hypothetical scenarios by varying the parameters analyzed and observing the effects of these changes on the final result. The following parameters were therefore evaluated for the scenario analysis: Transport - collection (+/- 10%) and emissions of ammonia, nitrous oxide, and methane (+/-10%), to the atmosphere, for scenarios SC1 and SC2, as carried out by Rotthong et al. [47]; Richard et al. [46] and Martinez-Blanco et al. [33]. These parameters were selected to carry out the sensitivity analysis as they greatly influence the impacts produced and avoided by these treatment systems [2. 5. 22, 27].

It also analyzed how the recovery of biogas produced at the landfill can contribute to the reduction of impacts arising from solid waste treatment since the João Pessoa landfill does not currently recover the biogas produced. In this way, the production of 0.166 kWh of electricity from the valorization of biogas produced in the landfill was considered [34].

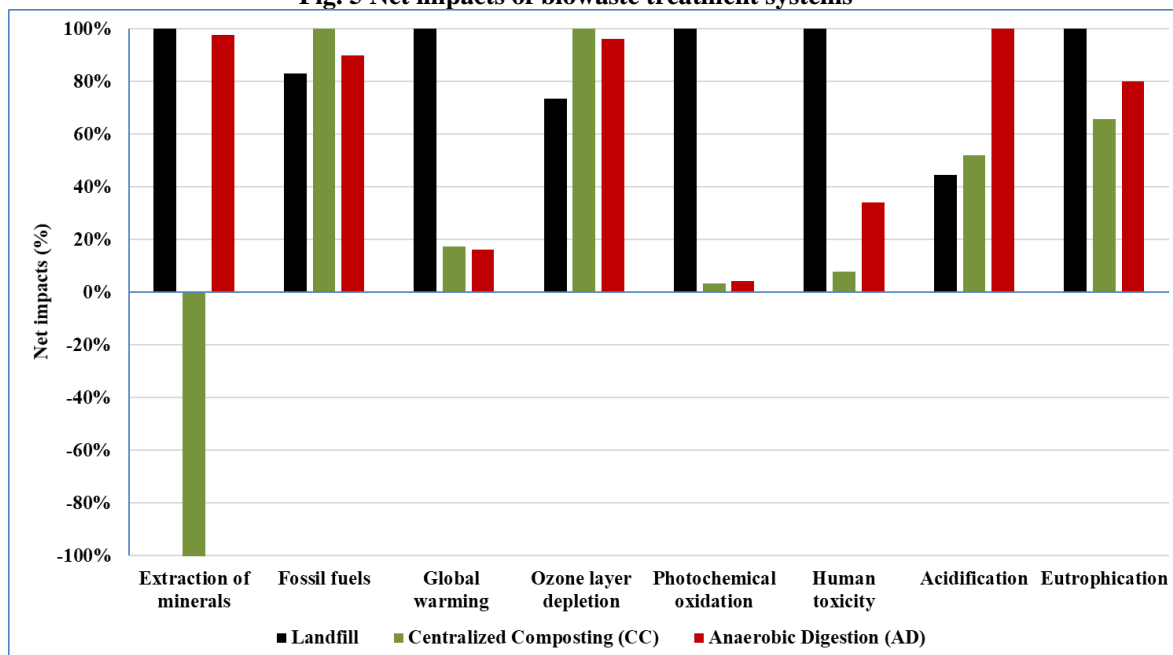
3. RESULTS AND DISCUSSION

3.1 Life cycle impact assessment

Figure 5 shows the net impacts of the centralized treatment systems evaluated. Upon examining Figure 5, it is possible to identify that the disposal of biowaste in landfill (SC0) is the most negatively impacting scenario for 62.5% of the categories analyzed, such as consumption of mineral resources, global warming, formation of photo-oxidants, human toxicity, and eutrophication. On the other hand, the destination of 100% of biowaste for centralized composting (SC1) had a higher impact on 25% of the categories analyzed: consumption of fossil fuels and ozone layer depletion. Anaerobic digestion (SC2) had a higher effect on the acidification category.

This result corroborates Guillaume et al. [22], Mersoni; Reichert[35], and Richard et al. [46], who show that landfills have a more significant impact on eutrophication, global warming, human toxicity, and the formation of photo-oxidants than scenarios that consider diverting organic waste to composting or anaerobic digestion. In this regard, Weidner et al. [53] calculate that the impacts of landfills on global warming are up to 3.5 times greater when compared to centralized composting and anaerobic digestion.

Fig. 5 Net impacts of biowaste treatment systems



Thus, segregating the biowaste produced in lodging facilities and disposing of it in centralized composting (SC1) or anaerobic digestion can reduce net impacts by 62.5% of the categories, such as consumption of mineral resources, global warming, formation of photo-oxidants, human toxicity, and eutrophication, when compared to disposing of biowaste in the landfill, along with the other MSW (SC0).

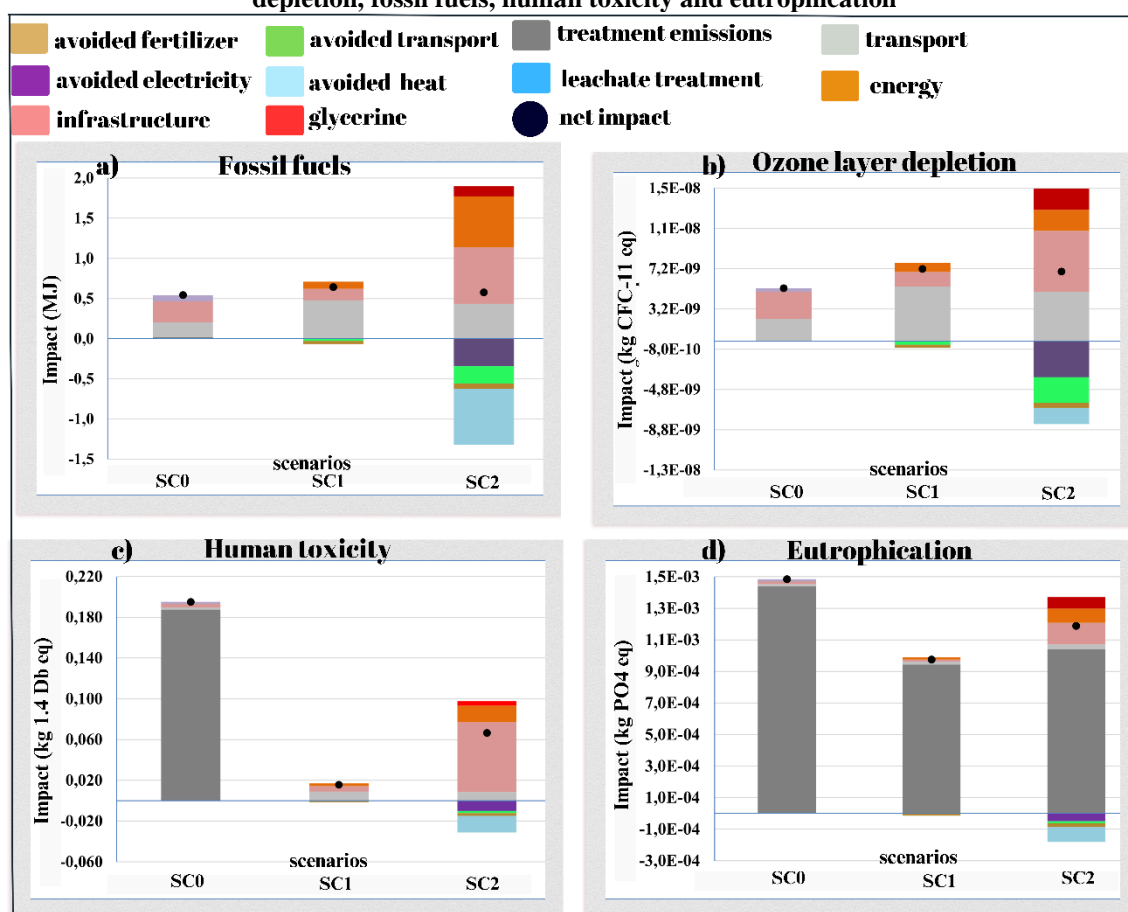
Of these reductions, centralized composting shows the utmost reductions in four categories: consumption of mineral resources, human toxicity, formation of photo-oxidants, and eutrophication, while AD has the highest reductions in global warming. Furthermore, in the categories in which the destination of biowaste to CC or AD shows an increase in impacts compared to landfill, anaerobic digestion is less impactful than centralized composting in ozone layer depletion and fossil fuels, while the opposite occurs in acidification.

Comparing anaerobic digestion with centralized composting, the first type of treatment has higher net impacts in 62.5% of the categories, such as consumption of mineral resources, human toxicity, acidification, and eutrophication. In comparison, CC has the highest impacts in 37.5% of the categories, such as consumption of fossil fuels, ozone layer depletion, and global warming. Composting is more negatively impactful in these categories due to the greater distance between the hotel sector and centralized composting compared to anaerobic digestion, which leads to more significant impacts on fossil fuel consumption and ozone depletion. In addition, the energy recovery of

organic waste through anaerobic digestion makes it possible to reduce the impacts of global warming, making composting more negatively impactful.

Figure 6 shows the contribution of each process to the net impact of the treatment systems. As Figure 6 illustrates, the destination of biowaste to centralized composting (SC1) had the highest net impact related to fossil fuel consumption (Figure 6a). This result is attributable to the choice to direct a specific collection of biowaste generated in the hospitality sector towards centralized composting or anaerobic digestion, with the composting facility situated at a greater distance. In this context, the impact resulting from the transportation of biowaste to the treatment and valorization by the centralized composting plant is equivalent to $4.81E^{-1}$ MJ, 63% higher compared to the regular transportation of MSW to the landfill.

Fig. 6 Contribution of processes to the net impacts of different treatment systems - ozone layer depletion, fossil fuels, human toxicity and eutrophication



The destination of biowaste for anaerobic digestion (SC2) showed the most significant impacts produced related to fossil fuel consumption, 1.89 MJ (Figure 6a), especially the use of thermal energy expressed through coal. However, disposing of

biological waste in AD provides energy recovery through the non-production of thermal and electrical energy, reducing the use of coal, oil, and natural gas, making it possible to reduce impacts by -1.32 MJ. This result corroborates Ardolino et al. [5] and Colón et al. [17], who state that recovering energy from biological waste reduces using natural gas and coal for energy production. In this way, the benefits of energy recovery outweigh the impacts produced.

A similar result was identified for ozone layer depletion, with the destination of biowaste to centralized composting being the most impactful scenario, $7,8E-9$ kg CFC-11 eq (Figure 6b). Similar to the case with fossil fuel consumption, this result is justified by adopting a specific collection of biowaste produced in the hospitality sector, which is longer for centralized composting plants than for anaerobic digestion and consequently more impactful (Figure 4). This result corroborates Ibáñez-Foréz et al. [26], who show that the regular collection of solid waste is one of the leading causes of impacts related to ozone layer depletion.

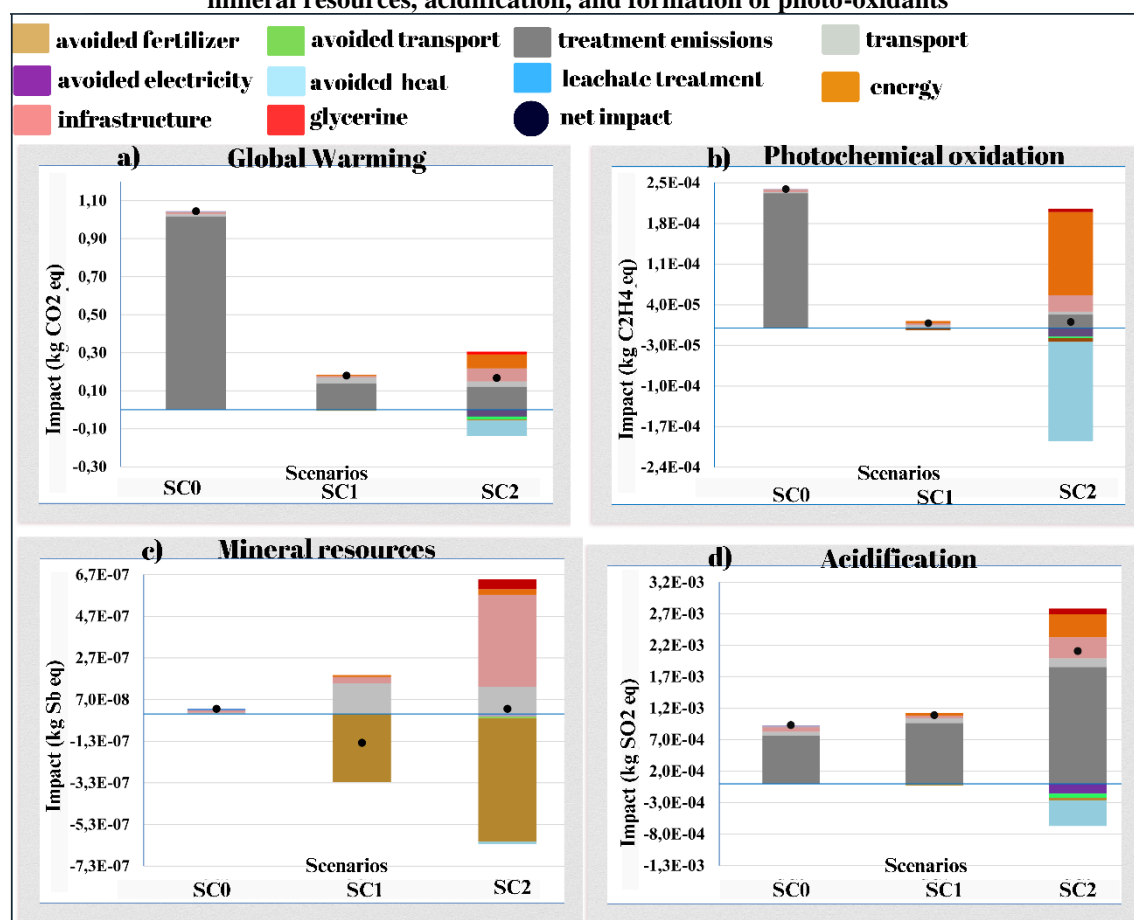
Another influential aspect was the reduction in energy production. The energy recovery of biowaste with AD makes it possible to reduce electricity production, reducing methane, bromine trifluoro-halon, and ethane trichloride trifluoride emissions, equivalent to -3.57 kg CFC11. There are also the benefits of reducing waste transportation to the landfill, with an avoided impact equivalent to -2.56 kg CFF11 due to the non-emission of Methane, Bromine Trifluoro-Halon.

Concerning human toxicity (Figure 6c) and eutrophication (Figure 6d), GHG emissions from the disposal of biowaste in the landfill stand out when compared to CC and AD, mainly due to emissions of barium and nickel, related to human toxicity, and the high concentration in biochemical oxygen demand (BOD) and emissions to water bodies of ammonia and nitrate, related to eutrophication. These results corroborate Richard et al. [46] and Boer et al. [9], who state that in addition to barium, lead, magnesium are other substances that cause higher impacts related to human toxicity and that the impacts related to eutrophication are mainly due to the leachate produced in landfills.

Therefore, for eutrophication, the SC0 scenario has a net impact of 52% and 25% higher than composting and anaerobic digestion, respectively. In comparison, for human toxicity, the landfill's impact is 1000% higher than composting and 190% more than anaerobic digestion.

Figure 7 shows the contribution of each process to the net impact of the treatment systems. Concerning global warming (Figure 7a) and photo-oxidant formation (Figure 7b), GHG emissions from biowaste disposal in the landfill account for the majority of net impacts, making the SC0 scenario the most impactful in these categories. Regarding the issue of global warming, GHG emissions from disposing of biowaste in CC or AD are approximately 90% lower than from landfills.

Fig. 7 Contribution of processes to the net impacts of different treatment systems – global warming, mineral resources, acidification, and formation of photo-oxidants



The energy recovery of biowaste provided by its AD treatment makes it possible to avoid the production of thermal energy and consequently reduce the emission of fossil carbon dioxide, thus reducing the impacts related to global warming. Similarly, energy recovery reduces the impacts related to the formation of photooxidants by reducing emissions of fossil carbon monoxide, sulfur dioxide, and biogenic methane.

This result corroborates Ardolino et al. [5] and Jensen et al. [27], who show that reducing fossil carbon dioxide and nitrous oxide emissions is the higher benefit of anaerobic digestion regarding global warming. They also agree with Guillaume et al.

[22], who state that energy recovery is the main contributor to the positive impacts of AD for the formation of photo-oxidants.

The landfill has the higher net impacts related to the consumption of mineral resources (Figure 7c), coming from the significant emissions of heavy metals such as lead and cadmium from the infrastructure and transportation. Due to its infrastructure, AD has the most impact produced, expressed through heavy metals such as lead and cadmium emission.

However, disposing of biowaste in AD or CC provides material recovery of biowaste through the non-production of conventional fertilizers, reducing the impacts produced by $-6.28E-7$ kg Sb and $-3.25E-7$ kg Sb, respectively, mainly due to the non-emission of cadmium, lead, silver, and zinc. This result corroborates Guillaume et al. [22] and Lima et al. [32], who emphasize that the positive impacts related to the consumption of mineral resources come from the avoided production of fertilizers through the non-emission of heavy metals. In this way, the net impact of disposing of biowaste in landfills is higher than the effects of disposing of these materials in centralized composting or anaerobic digestion.

The destination of biowaste to anaerobic digestion (SC2) was the most impactful scenario for acidification (Figure 7d) due to the emission of gases from waste treatment, such as ammonia. To compare, GHG emissions from waste treatment by centralized composting or landfill are 48% and 58% lower, respectively, compared to anaerobic digestion. This result corroborates the investigation from Khandelwal et al. [30], which shows that the acidification impacts of treating biowaste by anaerobic digestion are higher than composting and landfilling.

Thus, the results obtained from the life cycle impact assessment show that disposing of biowaste in landfills causes significant negative impacts compared to diverting the flow of this waste to centralized composting or anaerobic digestion. Global warming, human toxicity, photo-oxidant formation, and eutrophication stand out as the categories most affected by this inadequate disposal. It is, therefore, necessary to implement actions that encourage the detour of biowaste to other centralized treatment systems, such as centralized composting and anaerobic digestion.

Therefore, the disposal of biowaste from hotels in landfills, without any recovery of energy or materials, significantly impacts the environment. Furthermore, regarding net impacts, the disposal of biowaste in CC or AD reduces impacts in 62% of the categories analyzed, such as global warming and human toxicity.

This result corroborates Richard et al. [46], who state that diverting the flow of biowaste to centralized composting or anaerobic digestion can lead to significant reductions in the impacts of global warming, photo-oxidant formation, and eutrophication. Similarly, Boer et al. [9] indicate that the specific collection of biowaste, together with its treatment by anaerobic digestion, is capable of reducing environmental impacts related to global warming, acidification, eutrophication, and ozone layer depletion when compared to collecting this waste together with recyclable and non-recyclable waste and disposing of it in a landfill.

Thus, among the centralized treatments, the destination of biowaste from João Pessoa's hospitality sector to centralized composting is less impactful. The regionalization of the processes used to build the life cycle inventory is highlighted in an attempt to bring the scenarios closer to the reality of the study site, which is a limitation of LCA studies since not all processes can be regionalized.

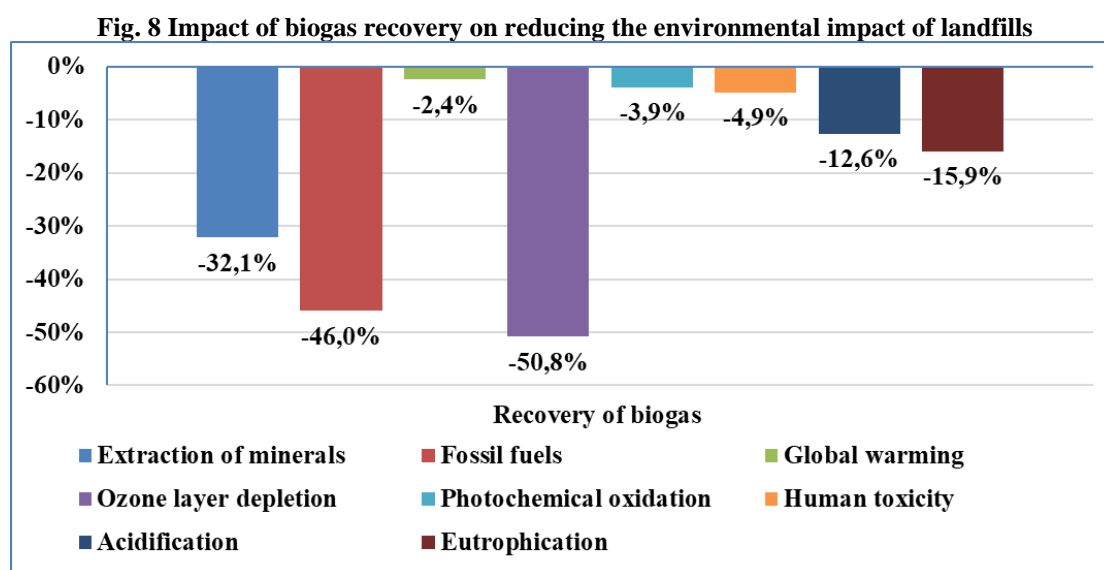
The results discussed here can serve as a basis for formulating public policies aimed at non-generation, reduction, and environmentally appropriate disposal of the waste generated in the city of João Pessoa since the solid waste generated in the city is currently disposed of in the landfill without any material or energy recovery. In this sense, the management of organic waste from the hospitality sector, with proper segregation at the source of generation and its subsequent recovery, can act as a primary project that can then be expanded to other economic activities and, in the future, to municipal solid waste.

3.2 Sensitivity analyses

This sensitivity analysis has been carried out by varying the transportation parameters related to the collection of biowaste (+/-10%). Emissions to the atmosphere of ammonia, nitrous oxide, and methane (+/-10%), as well as analyzing how the recovery of landfill biogas would reduce the impacts of this scenario since there is currently no such recovery.

The scenario analysis shows that the recovery of biogas produced in the landfill would be able to reduce approximately 50% of the impacts related to the ozone layer depletion and the consumption of fossil fuels, as well as reducing the impacts related to the consumption of mineral resources by 32%, eutrophication by 16% and acidification by 13% (Figure 8). Therefore, if it is impossible to treat biowaste by composting and

anaerobic digestion, it is necessary to implement tools to recover the biowaste disposed of at the João Pessoa landfill, providing biogas recovery through energy production.



The variation in the biowaste transportation route for scenario SC1 shows that increasing/reducing the transportation route by 10% will result in a variation of +/-10% in the net impacts relating to the extraction of minerals, 8% to fossil fuel consumption, and ozone layer depletion, as well as +/-5% for global warming. A similar result was identified in the analysis of scenario SC2, with a 10% increase/decrease in the transportation route resulting in a variation of +/-13% in the net impacts related to extraction of minerals, +/-8.2% to fuel consumption, +/-7.5% related to ozone layer depletion and +/- 4.8% related to global warming (Table 3).

Table 3 Effect of varying the collection route and emissions on the impacts of composting and anaerobic digestion

Categories	Centralized composting		Anaerobic Digestion	
	Transport	Emissions	Transport	Emissions
Fossil Fuels	+/- 8.5%	-	+/- 8.2%	-
Global Warming	+/- 4.6%	+/- 15.9%	+/- 4.8%	+/- 15.7%
Ozone Layer Depletion	+/- 8.4%	-	+/- 7.5%	-56

Concerning the variation in the emission of ammonia, nitrous oxide, and methane into the atmosphere in the SC1 and SC2 scenarios, significant changes were only observed in the impacts of global warming and human toxicity for SC2. Thus, for both CC and AD, a 10% increase/reduction in emissions of these GHGs will result in a

variation of approximately +/-16% in the net impacts related to global warming and +/-12% in human toxicity (Table 3).

In this way, the sensitivity analysis indicates that it is essential that the data used to construct the life cycle inventory is as accurate as possible, especially concerning greenhouse gas emissions, which are difficult to collect primarily.

4. CONCLUSION

The life cycle assessment of different scenarios for the centralized management of biowaste from the hospitality sector in João Pessoa showed that disposing of biowaste in the landfill, the current situation in the city of João Pessoa is the scenario that causes the most damaging environmental impacts while disposing of biowaste in centralized composting is the least impactful scenario. Therefore, regarding environmental impact, centralized composting would be a suitable scenario for treatment of biowaste from João Pessoa's hospitality sector. This result can serve as a basis for other tourist regions to develop research that includes organic waste from potential large solid waste generators in their analysis, such as street markets, supermarkets, and restaurants since the most common approach is to deal with MSW or household solid waste.

It was also observed that the optimization of transport and control of emissions, as well as the recovery of landfill biogas, can reduce the environmental impacts related to the treatment of biowaste through composting (SC1) and anaerobic digestion (SC2), in addition to those resulting from the current management of this waste (SC0). Therefore, it is necessary to implement actions that promote the detour of the flow of biowaste to other centralized treatment systems, such as industrial composting or anaerobic digestion.

Therefore, the research makes it possible to identify the main negative environmental impacts of the current organic waste management system and the benefits of diverting the flow of this waste to more appropriate systems, such as composting and anaerobic digestion. Finally, this study facilitates the proposal of tools and the development of management strategies, including the stages of collection and transportation, treatment, and, above all, the recovery of organic waste.

For future research, it is recommended that other significant generators of organic waste be added to the hospitality sector, such as restaurants, street markets, and supermarkets, so that it is possible to analyze the changes resulting from the increase in

biowaste production. Furthermore, it is recommended that future research carry out an economic analysis of how biowaste's energy and material recovery can be used to offset the construction costs of these facilities. In addition, it is recommended that the decentralized management of biowaste and its influence on reducing environmental impacts be analyzed, for example, by implementing home or community composting.

5. DECLARATION OF INTEREST STATEMENT

The authors report that there are no competing interests to declare.

6. FUNDING DECLARATION

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7. AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by Igor do Nascimento QUARESMA, Gilson Barbosa ATHAYDE JÚNIOR, Audrey TANGUY Mariana Moreira DE OLIVEIRA, Igor BELLI, and Rémy BAYARD. The first draft of the manuscript was written by Igor do Nascimento QUARESMA, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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