Processing of Biomethane for Electricity Production as a Sustainable Way to Treat Municipal Organic Solid Waste: A Case Study of the Corumbataí River Basin Region

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This study proposed action scenarios for urban solid waste management in six municipalities in the Corumbataí River Basin. The operating scenarios were designed for organic waste treatment and for the shared disposal of urban solid waste. Six municipalities were studied, five of which had less than 30,000 inhabitants (Analândia, Charqueada, Corumbataí, Ipeúna, and Santa Gertrudes). In addition, Rio Claro had 199,000 inhabitants. Thus, the transport and transshipment stages, general infrastructure, and final disposal in landfills were analyzed. Further, the three scenarios for organic waste treatment were conducted separately. The items and the cost of implementation were estimated for decentralized composting, centralized composting, and biomethanization of waste with electricity recovery. The biomethanization scenario included the commercialization of electricity, so it generated revenues that decreased costs. This cost reduction was especially notable in the last years of the project when the goals of diversion of organic waste through selective collection were higher. The results suggested that the investigated scenarios could improve organic waste treatment and that the biomethanization scenario with electricity generation presented lower average costs per inhabitant than the centralized and decentralized composting scenarios.

Keywords: Biomethane processing; Waste management; Biomethanization; Composting scenarios; Bioeconomics

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INTRODUCTION

In most Brazilian municipalities, the waste management process involves only simple collection, transportation, and final disposal activities, which can occur in landfills, controlled landfills, or open dumps. In these three cases, the material is simply deposited, which can be reasonable under certain circumstances. However, in many situations, such practices can have different levels of impact on the environment and cause a financial imbalance.

In Brazil, the data on the final disposal of solid urban waste reveals that 59% of collected waste is sent to landfills. A total of 10% is sent to controlled landfills, 10% is sent to landfills, 3% is sent to sorting and composting plants, and there is no information on where the remaining 18% is sent. The portion with no information is mostly composed of municipalities with up to 30,000 inhabitants. Municipalities of up to 30,000 inhabitants represent 80% of Brazilian municipalities (MCIDADES 2018).

In this regard, municipalities with up to 30,000 inhabitants deserve special attention, as these municipalities are the population group that presents the greatest difficulty in collecting data to characterize waste conditions, have lower rates of regular collection, have a larger rural population without collection services, have the smallest budgets to deal with problems related to waste issues, have the worst working conditions for handling waste, have a higher percentage of municipalities with dumps (MCIDADES 2017), and have a lower percentage of municipalities with selective collection (IPEA 2012). In addition, small municipalities have difficulties with the final disposal of waste due to high costs and poor technical capacities. Especially in São Paulo, this difficulty led to the dependence of small municipalities on large companies that operate private landfills. Therefore, there is a need for high quality final disposal, but such services would cause small towns to have higher costs and leave them without the means to treat their waste.

In this context, inter-municipal consortia are a means of economizing scale and accessing federal financial resources. Consortium initiatives can have advantages in relation to the actions of isolated municipalities for receiving federal resources. Nationwide programs would help to finance these activities similarly to the field of alternative energies (Strachotová *et al.* 2019). Smaller municipalities are more likely to participate in consortia for waste management in Brazil to share costs and profit from the scale of production through the rationalization of resources and the realization capacity of the municipalities (Cruz 2001).

The organic fraction of waste represents 51% of waste produced in Brazil (IPEA 2012). Thus, efficient use of the organic fraction could reduce the amount of waste sent to landfills. The National Solid Waste Policy (MMA 2012) establishes that the municipal plan must plan the implementation of composting systems for the organic fraction of its residues. However, only a small part is allocated to composting or other types of waste treatment.

Composting and biomethanization are treatment processes for organic waste *via* biochemical conversion (Williams *et al.* 2003). Natural composting is carried out by disposing waste on windrows (elongated piles of material), in which the aerobic digestion of organic material occurs (MMA 2010). Biomethanization is the process of anaerobic digestion with the recovery of renewable energy from the burning of methane present in the resultant biogas (Lino and Ismail 2015; Matos *et al.* 2020).

The investigated municipalities were chosen because they had the potential for shared action to carry out solid waste management services. The five municipalities ranged in population from category 1 (up to 30,000 inhabitants) to a population category of 3, which included Rio Claro (100,000 inhabitants to 250,000 inhabitants) (Table 1). The municipalities make up a sub-basin of the Piracicaba River. Therefore, they are part of the Water Resources Management Unit (UGRHI 5) (Fig. 1).

This study aimed to identify operational strategies for the shared management of urban solid waste generated in the six municipalities in the hydrographic basin of the Corumbataí River. This work was prepared based on the composition and financial estimate of operating scenarios for the management of household solid waste by treating separately collected organic waste. Through identifying action strategies, this work aimed to facilitate effective decision-making in waste management in the municipalities studied and thereby contribute to solving similar problems in other municipalities with similar characteristics.

Table 1. Population and Waste Generation in the Municipalities Studied

Municipality	Total Population	Urban Population	GDP *per capita*
	Hab	Hab	R$/hab.ano
Corumbataí	4,054	2,191	24,506.35
Analândia	4,845	3,847	28,983.51
Ipeúna	7,177	6,177	86,883.95
Charqueada	16,772	15,216	15,988.52
S. Gertrudes	25,637	25,364	64,130.83
Rio Claro	202,952	198,012	42,613.74

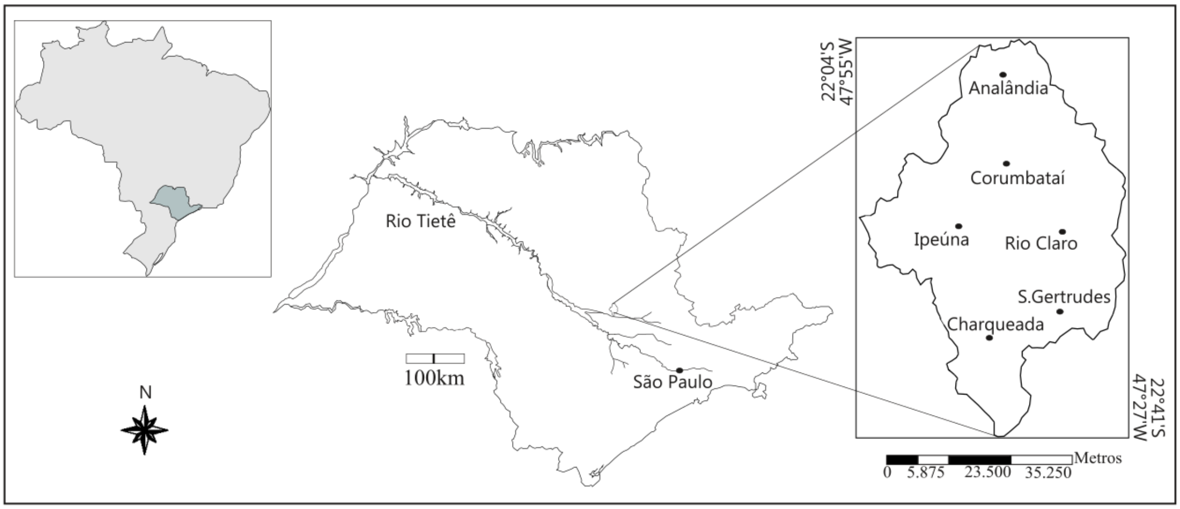

Fig. 1. Location diagram of the Corumbataí river basin and the headquarters of the municipalities

The selective collection of organic waste must be structured with segregation planning at the source. This step is important, as the separation of waste by users determines the quality of the compost at the end of the process. In this phase, the city collects organic waste previously selected by users in a specific collection truck for this purpose. The scope of organic collection was designed to gradually expand *via* progressive achievement of goals for 20 y and not be grinded during the process. The targets represent the diversion of organic waste previously separated by users for treatment, recyclable materials were not account in this study. The amount of organic waste was determined at 51.4% (IPEA 2012) of the total waste produced. Private and public yard waste was not considered for this study. The target for diversion of organic waste started at 35%, rises to 50% in 2025, further increases to 75% in 2030, and 100% in 2035.

Due to human activity, waste accumulation is a global problem (Rozenský *et al.* 2019). In addition, the dumping of municipal waste releases greenhouse gases into the atmosphere, which leads to a chain of ecological threats caused by human activity (Hájek *et al*. 2019). Palafox-Alcantar *et al.* (2020) conducted specific theoretical research on waste management. Heidari *et al.* (2018) and Chen *et al.* (2019) worked with progressive game theory. This study dealt with a case study in a specific Brazilian region and addressed specific local problems. Similar national or regional studies have been conducted and published by Bui *et al.* (2020) in Vietnam, Chen *et al.* (2017) in China, and Garofalo *et al.* (2019) in Italy. Among other things, this study also dealt with the costs and economic aspects of the investigated landfill solutions. Ferramosca (2019) and Michael and Elser (2019) also dealt with this issue. In addition, Bilgili (2020) examined this topic, which was an environmental and economic analysis of waste management scenarios for a warship from a life cycle perspective. This study also addressed the treatment of landfill gases, which is an important tool in air and climate protection. The issue of landfill gas release and utilization has been investigated by Bel Hadj Ali *et al.* (2020), Rahimi *et al.* (2020), Kim *et al*. (2018), and in a specific study from the Eastern Amazon by Imbiriba *et al.* (2020). Further, regional research on this topic has been published by Mihajlovi *et al.* (2016), Sun *et al.* (2019), or Fei *et al.* (2019).

Materials and Methods

The area that received the treatment was selected by Oliveira (2008). The selected area was a portion of the land that was geologically compatible with a sanitary landfill, and it was located in the Ajapi neighborhood in the municipality of Rio Claro in the central portion of the Corumbataí River Basin. The municipality of Rio Claro accounted for 79% of the total household waste generated in the municipalities, and it was spatially located in the center of the basin. In the studied scenarios, the collection stage was the responsibility of the municipalities and consisted of regular collection, which involves the collection of mixed waste and selective collection of the organic fraction separated at the source. City halls forwarded collected waste to transshipment stations in each municipality. From the transshipment stations, shared management trucks transported organic waste to treatment sites, and waste from regular collection was transported to the landfill, and it was located at the Treatment and Final Disposal Center in Ajapi.

From the CTDF, three scenarios were proposed and selectively collected for the treatment of organic waste, which were aerobic treatment by natural composting performed centrally at the CTDF, aerobic treatment by natural composting done in a decentralized manner next to the transshipment stations in each municipality, and anaerobic treatment by biomethanization with electricity commercialization generated from biogas. Figure 2 presents the explanatory diagram of the research.

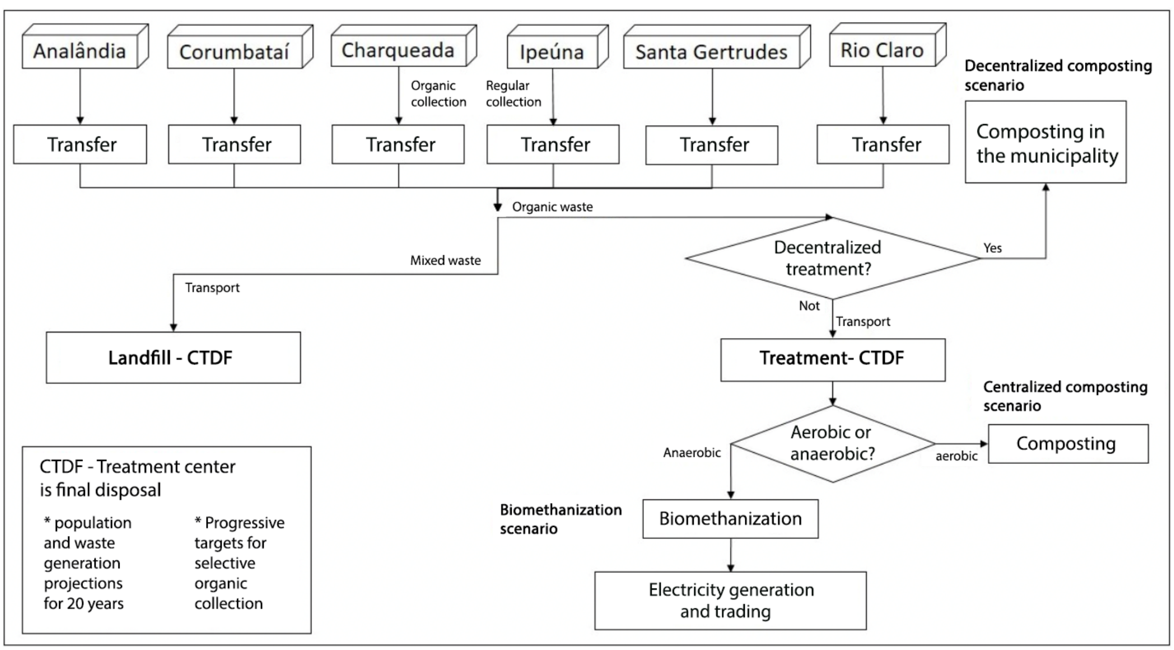

Fig. 2. Explanatory diagram of the proposed scenarios for shared waste management in municipalities based in the Corumbataí River Basin

Progressive targets for the diversion of organic waste from the landfill for treatment were stipulated. These goals began in accordance with the targets stipulated by the National Solid Waste Plan (MMA 2012). The targets represented the diversion of organic waste previously separated by users for treatment. The amount of organic waste was determined as 51.4% (MMA 2012) of the total waste produced. The target for diversion of organic waste started at 35%, and it will rise to 50%, 75%, and 100% in 2025, 2030, and 2035, respectively.

Each municipality had a transshipment station and sent its waste to a plant. As such, each transshipment site needed to be able to receive and deliver organic waste and mixed waste. Thus, the transshipment stations were planned so that the trucks of the shared management could collect the material for it to be transported to the treatment center. For the treatment of organics by decentralized composting, the sizes of the transshipment stations were increased to accommodate the composting yard to meet the demand of the municipality.

To meet the project's demand, the costs of general waste infrastructure were investigated. These expenses are common in the waste treatment stage and the final disposal stage of regular collection residues. Thus, they make up a fraction of the valuation of the scenarios produced in this research. Each of these fractions is detailed in the following sections.

The dimensions of the landfill were set according to the population and waste generation projections, and the goals for the diversion of the organic portion for treatment were determined. The following section describes the methodology used to develop the population growth and waste generation projections.

Projections of Population Growth and Waste Generation

To determine the values involved with the studied scenarios, population and waste generation projections were necessary. These projections were made to estimate the population and the waste generation of the municipalities investigated over 20 y from 2019 to 2039.

To project the population, the data used were extracted from the database of the Brazilian Institute of Geography and Statistics (IBGE 2002, 2012) from 1980, 1991, 1996, 2000, 2007, and 2010. For the waste generation projection, data from the National Sanitation Information System (MCidades 2017) from 2008 to 2016 was used.

To perform the projection calculations, the methodology used was presented by the Ministry of the Environment (2013), who presented four different calculation methods, which included the arithmetic method, the geometric method, the least squares method, and the graphical correlation method. The methods were applied individually for each municipality.

To analyze the results obtained, the Pearson correlation coefficient (R^2) was applied, which measures the degree of correlation between the projections and the available data. The Pearson correlation coefficient varies from -1 to 1, and values closer to 1 indicate a greater correlation. The method with the highest R^2 value was chosen.

Composition and Costing of Shared Management Scenarios

In this stage, the needed items that comprised the expenses and their respective cost values were investigated for the implementation and operation of the shared management proposal and the scenarios for the treatment of the organic waste collected separately. The costs were raised for 20 y. Additionally, they were divided into implantation expenses (necessary once in the beginning or when the demand increased) and operating expenses (costs that recur annually).

Thus, tables were prepared for the presentation of expenses from transshipment and transportation, general infrastructure, landfills, the scenario for the treatment of organic waste by centralized composting, the scenario of treatment of organic waste by decentralized composting, and the scenario of treatment by biomethanization. Figure 12 is an explanation of how the expense figures were grouped and calculated.

All steps included expenses, such as the maintenance of equipment and installations and expenses related to purchasing new equipment after its useful life. Maintenance costs were determined as 85% of the equipment's value over its useful life and 25% of the value of the facilities over the project's duration according to the methodology presented by the Ministry of the Environment (MMA 2010). The amounts, in Reals (R$), were taken from several sources, which included the bank of prices for work and engineering services published by the Basic Sanitation Company of the State of São Paulo (SABESP 2018), quotes from specific equipment sellers, and quotes with the average of three current market prices in November 2018. The methods used in each cost composition stage are described below (Fig. 3). The stages are divided into expenses of implementation and annual operation expenses.

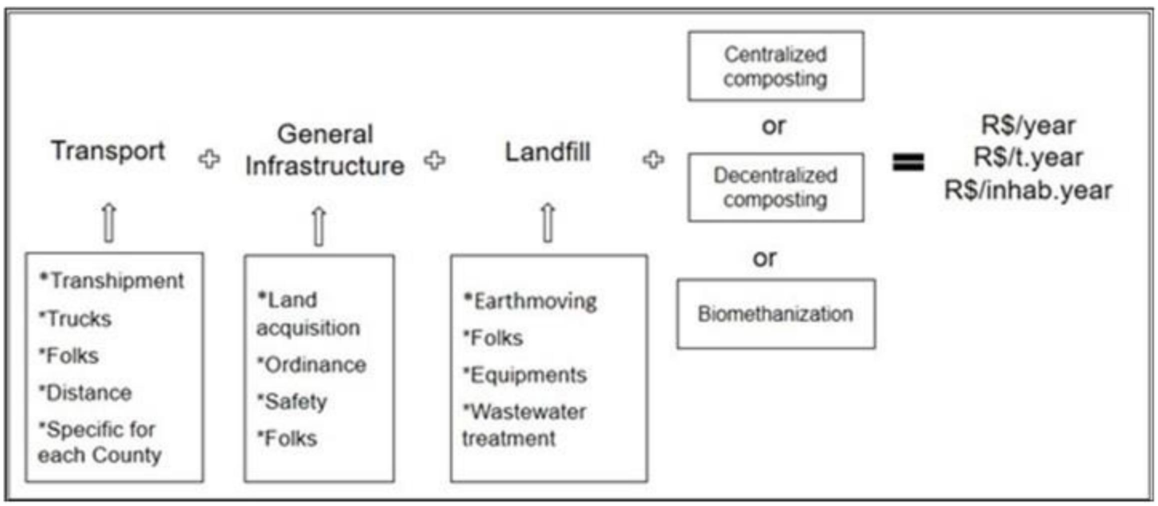

Fig. 3. Calculation process for determining the total waste by municipality and by treatment of organic waste

The transshipment and transportation expenses were related to the installation of transshipment stations in all municipalities and the acquisition of two types of trucks, one of which was used to handle waste collected by regular collection, and the other was used to transport organic waste that was collected separately. The municipalities of Analândia and Corumbataí shared the trucks due to their small population. The costs of operating the transport included personnel expenses, truck fuel and maintenance, and the facilities of the transshipment stations. Truck maintenance was defined as 100% of the amount spent on fuel. Transport expense calculations were performed individually for each of the six municipalities studied.

The general infrastructure costs referred to the activities in common that were carried out in the various stages of the scenarios analyzed in this research. The items for the implementation of general infrastructure included land acquisition, the licensing process, and support facilities, such as concierge, fencing, and security. The operating items of the general infrastructure included the payment of personnel, such as doormen, scale operators, security personnel, and engineers responsible for the plant. These operating costs also included expenses related to the maintenance of both equipment and facilities in addition to electricity.

The implementation and operation of a common landfill among the six municipalities were analyzed. The dimensions of the landfill were determined based on the estimated generation values for the 20 y of the project and the targets for diversion of organic waste for treatment. The implantation costs referred to the expenses of earthmoving and the preparation of the land, which included the acquisition of machinery and equipment. These costs also referred to the expenses from the treatment of gaseous and liquid effluents. The landfill implantation values were divided into five levels over the 20 y. The expenses related to landfill operation were related to the payment of employees for supervision of machinery operation and assistance with general services and yard services. In addition, operating costs included fuel and maintenance of equipment and facilities.

Organic Waste Treatment

Expenses related to organic waste treatment scenarios were considered in accordance with the projected generation of waste and the progressive targets for the diversion of organic material collected separately and planned to increase every 5 y. The methodology used to determine the costs of the two proposed scenarios for the treatment of organic waste is described below.

Treatment Scenarios with Centralized and Decentralized Composting

For the treatment of organic waste segregated at the source, a scenario was developed with the application of natural composting technology from the volume raised in the diagnosis stage (Luz 2019). The methodology presented in the *Manual for Implementation of Composting and Selective Collection in the scope of Public Consortia* (MMA 2010) was chosen. This document is a product of the Water Resources and Urban Environment Secretariat of the Ministry of Environment / MMA within the scope of the International Technical Cooperation Project for the improvement of Urban Environmental Management in Brazil. This document provides technological guidelines for the natural composting of organic waste (MMA 2010).

To achieve natural composting of organic waste, the dimensions of the yard were determined according to the treatment demand in line with the goals presented above. Natural composting occurred in the yard *via* periodic turning of the windrows by specific equipment coupled with the tractor. The yard was designed so that the material would remain for 120 d with windrows that were 1.2 m tall and 1.2 meters wide. The triangular section of the windrow area, windrow volume, windrow length, and windrow dimension were determined according to Eq. 1, Eq. 2, Eq. 3, and Eq. 4, respectively,

$$A = (H \times L) / 2 \tag{1}$$

where A is the area of the triangular section (m^2), H is the windrow height (m), and L = windrow width (m),

$$V = P / d \tag{2}$$

where P is weight (kg), and d is density (kg / m^3),

$$C = V / A \tag{3}$$

where C is length (m), V is volume (m^3), and A is section area (m^2),

$$D = L \times W \times H \quad (4)$$

where D is the windrow dimension (m^3), W is the windrow width (m), and H the windrow height (m).

To calculate the yard area, a turning space equal to the space occupied by the windrow was considered along with an additional 10% for operation and circulation. After determining the dimensions of the facilities and listing the materials, the implementation and operating expenses were estimated in order to obtain a cost value per quantity of waste treated.

For the decentralized composting scenario, values for the implementation and operation of the composting system and overflow stations were estimated for each municipality investigated. Thus, each municipality would have machinery and personnel to perform the composting process without organic waste being transported to the Rio Claro plant.

The costs of implementing compost-treatment scenarios included expenses related to the construction of a waterproofed patio and the purchase of machinery, equipment, and the irrigation system for the windrows. Expenses related to the operation of the organic waste treatment system with composting included personnel, fuel, maintenance costs, and the purchase of new equipment and machinery to meet growing demand. The cost of diesel consumption by tractors was taken from Lopes *et al.* (2003).

Biomethanization Treatment Scenario

The scenario for the treatment of organic residues by biomethanization was designed to receive the residues from the selective collection of organics and treat them through anaerobic biodigestion *via* the recovery of the methane contained in the biogas resulting from the process.

The expenses involved in the implementation of this scenario involved the implementation of the initial system, the increase in the number of biodigesters as the selective collection of organics increased over the 20 y of study, the installation of a well for a water supply, and a drying yard. Operating expenses referred to personnel and the maintenance of facilities and equipment.

The biodigester chosen was a Canadian model, continuous flow tubular biodigester, with solids separator and hydraulic retention time of 30 days. This biodigester was chosen because it is a simple model, with application in Brazil. The dimensions of the biodigesters and the values for the acquisition of the biodigesters and generators were reported by Montoro *et al.* (2017).

This scenario provided for the generation and commercialization of electric energy as a revenue to reduce costs. The calculations for estimating electricity generation were developed according to the findings of dos Santos *et al.* (2019). Estimation of the amount of biogas produced in the digesters was performed using the following equations,

$$Qbp = G \times Mbp \quad (5)$$

where Qbp is the quantity of biogas produced (m^3/d), G is the amount of organic waste (ton/d), and Mbp is the average amount of biogas produced (m^3/ton). Equation 6 is as follows,

$$Qbc = Qbp \times Ecol \quad (6)$$

where Qbc is the quantity of biogas collected (m³/d), and $Ecol$ is the collection efficiency (90%) (Faulhaber *et al.* 2012).

The average amount of biogas produced (m³/t) was 119 m³/t, which was also proposed by dos Santos *et al.* (2016), who used this value to estimate the potential for generating electricity from solid organic waste in Brazil.

Thus, an electricity generation value was estimated by burning the methane contained in biogas obtained from organic waste in the municipalities studied. From this process, the methane generation potential was determined as 65% of the biogas produced (Persson *et al*. 2006), the calorific value of the methane used was 22 MJ/m³ (Guerini Filho *et al*. 2018), the energy efficiency of conversion into an internal combustion engine was 33% (Leme *et al*. 2014), and the capacity to convert the engine into electrical energy was 80% (Fiesinger 2015). Thus, the potential for generating electricity was obtained using the following equations,

$$Pa = Qbc \times \lambda \times PC \quad (7)$$

where Pa is the rated power (w), λ is the energy efficiency of conversion into an internal combustion engine (%), and PC is the calorific value of methane (Kj/m³).

$$E = Fc \times Pa \times 8{,}760 \quad (8)$$

where Fc is the conversion factor of the motor into electrical energy.

RESULTS AND DISCUSSION

The highest values of Pearson's coefficient (R^2) for all municipalities were obtained by the least squares method for the projections of population growth and waste generation. Figure 4 shows the results obtained for population projection and for waste generation.

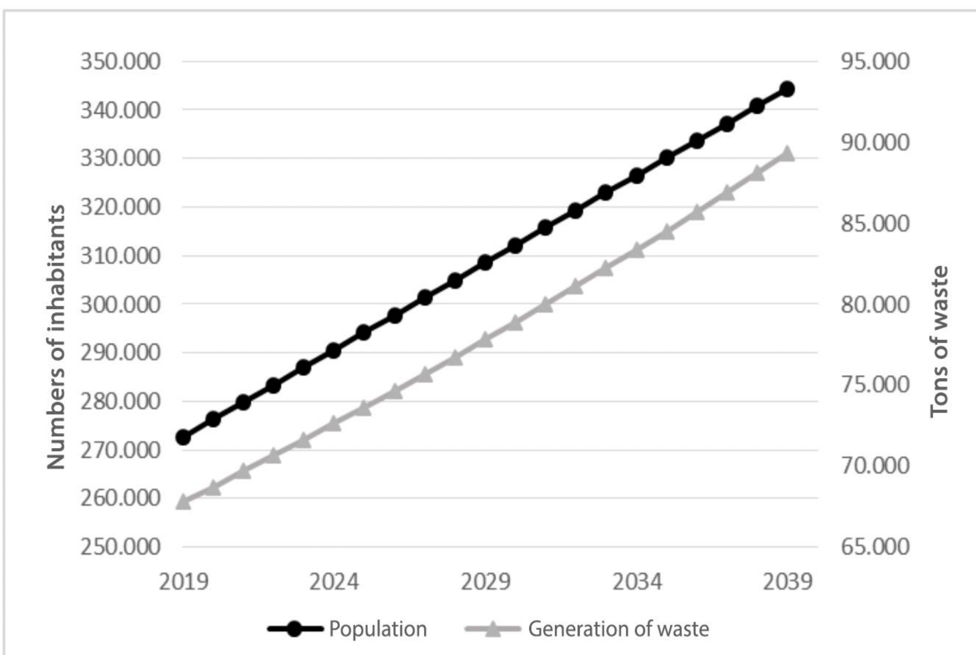

Fig. 4. Projections for population growth and waste generation obtained by the least squares method

Thus, the projection values presented were used to estimate the costs of the proposed scenarios according to the methodology presented above. The results were grouped into expenses from the implantation and operation (i) of the transshipment stations and the transportation of the waste to the CTDF, (ii) the general infrastructure for the operation of the treatment center, (iii) the shared landfill, (iv) the organic waste treatment scenarios by centralized and decentralized composting, and (v) the organic treatment scenario by anaerobic digesters. Figure 5 presents a comparative graph between the average costs of transshipment and transportation of all the municipalities studied.

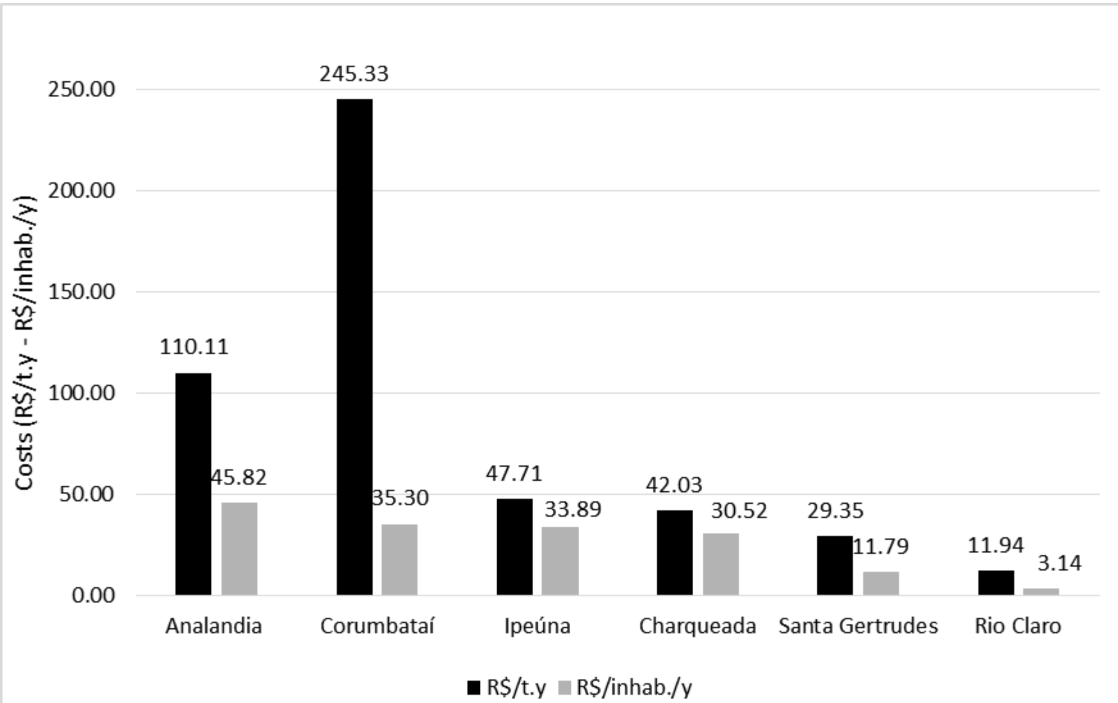

Fig. 5. Average expenses of transshipment and transportation for each of the municipalities

The lowest values were from Rio Claro, which was the largest municipality with the shortest distances between the generation center to the place of waste treatment, followed by its closest municipalities. The highest values per ton were found for Corumbataí, which has had selective collection of recyclables for 20 y (Luz 2019). This reduced waste generation per inhabitant, which caused this high value for the transportation of waste per ton. However, value per inhabitant was not as high. Analândia, the most distant municipality had the highest value per inhabitant.

Annual costs per ton and per inhabitant were calculated for the stages of shared management and for individual municipalities. The expenditures on general infrastructure, landfills, and treatment scenarios for the organic fraction collected separately were the same for all municipalities. The results of the estimated values for transport and the final values were different for each of the municipalities investigated, as they depended on the distance from the collection centers to Ajapi, a neighborhood in the municipality of Rio Claro that is located in the center of the basin.

The values of the first years were higher, as they included the expenses of implantation necessary to begin the operations. Variation in the values occurred according to the need for new investments to meet demand or to replace equipment at the end of its useful life. Table 1 shows the estimated values for the expenses of implementation and operation of the general infrastructure stages, landfills, and organic waste treatment scenarios through composting and biomethanization.

Table 2. Values per Ton and per Inhabitant for the Expenses of General Infrastructure, Landfills, and Organic Waste Treatment by Centralized Composting and Biomethanization

	General Infrastructure		Landfill		Centralized Composting		Biomethanization	
	R$/t.y	R$/hab.y	R$/t.y	R$/hab.a	R$/t.a	R$/hab.y	R$/t.y	R$/hab.y
2020	112.11	31.94	44.72	10.45	180.84	9.27	327.07	34.53
2021	7.06	2.05	13.55	3.22	139.18	7.26	41.49	3.62
2022	6.85	2.02	13.15	3.18	135.12	7.18	39.80	3.15
2023	6.66	2.00	12.77	3.14	131.30	7.09	97.58	7.25
2024	6.47	1.97	43.84	9.93	114.62	8.98	48.43	4.75
2025	6.29	1.95	13.33	3.07	87.63	6.97	25.31	2.50
2026	6.13	1.93	12.98	3.03	85.37	6.89	24.23	2.26
2027	5.97	1.90	12.64	2.99	83.22	6.82	23.20	2.13
2028	5.82	1.88	39.43	9.47	103.57	8.60	98.33	9.13
2029	5.68	1.86	14.54	2.92	53.55	6.76	13.17	1.86
2030	5.54	1.84	14.19	2.89	52.50	6.71	74.68	10.65
2031	5.41	1.82	13.86	2.86	51.15	6.62	11.83	1.71
2032	5.29	1.80	43.32	9.04	63.43	8.30	11.21	1.63
2033	5.17	1.78	13.24	2.79	49.30	6.53	68.48	10.07
2034	5.06	1.76	16.38	2.76	36.51	6.52	22.33	4.42
2035	4.95	1.74	16.03	2.73	35.77	6.45	22.97	4.59
2036	4.85	1.72	50.19	8.65	44.28	8.07	6.25	1.26
2037	4.75	1.70	15.37	2.68	34.39	6.33	5.80	1.18
2038	4.65	1.68	15.06	2.65	33.74	6.27	5.37	1.10
2039	4.55	1.66	14.75	2.62	33.09	6.22	4.91	1.02
Ave	**10.96**	**3.35**	**21.67**	**4.55**	**77.43**	**7.19**	**48.62**	**5.44**

The average results per ton and per inhabitant were grouped by scenario to allow comparison of the estimated values by municipality. Figures 6 and 7 show the average values found for the three scenarios investigated for each of the six municipalities.

The average results of costs per ton revealed that the values were higher for municipalities with the smallest populations, which were Analândia and Corumbataí. The centralized composting scenario yielded the highest values per ton, except for in the municipalities of Corumbataí and Analândia.

The decentralized composting scenario had the highest values per inhabitant for all municipalities. The scenarios of centralized composting and biomethanization had similar values per inhabitant for all municipalities. The municipality of Rio Claro had the lowest values per ton and per inhabitant. This municipality included 79% of the total population of the municipalities studied.

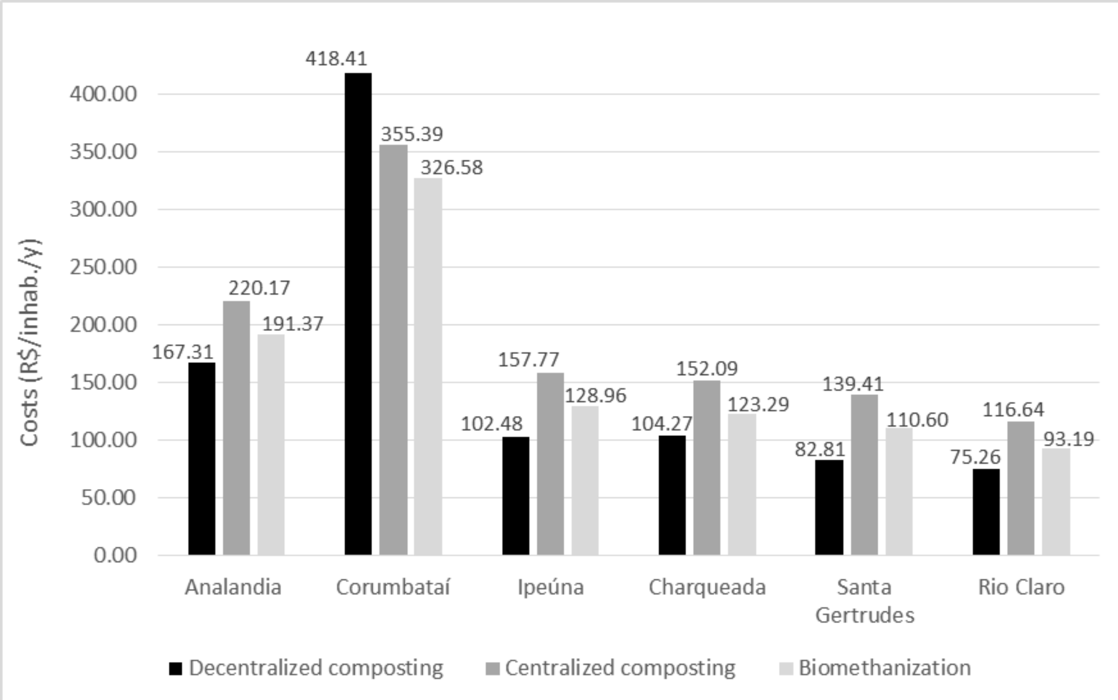

Fig. 6. Estimated average values for the implementation and operation of the investigated scenarios for the municipalities studied

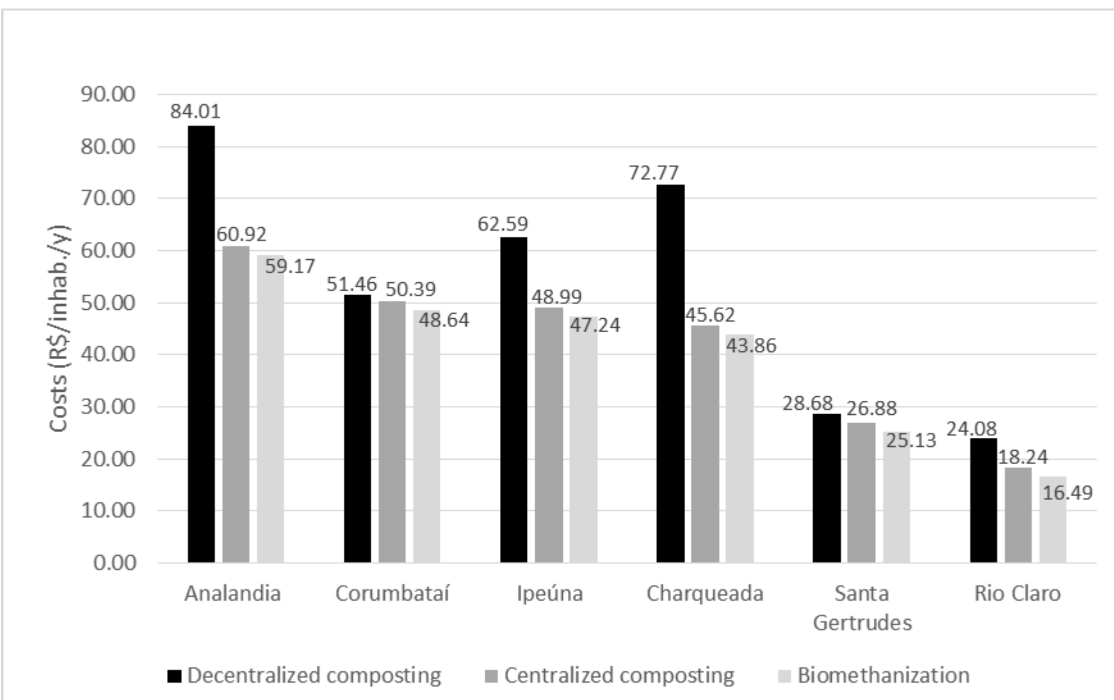

Fig. 7. Estimated average values for the implementation and operation of the investigated scenarios for the municipalities studied

The results showed that, despite being more expensive per ton, the biomethanization treatment scenario had the advantage of producing electricity. With the increase in the amount of organic waste diverted to treatment, the expense amounts can be covered by revenues. In this sense, more studies are needed to investigate the amount of waste and production duration necessary for this method to become profitable instead of just treating waste.

The results from the scenarios of waste treatment by centralized and decentralized composting indicated that these simple systems were effective solutions for the treatment of organic waste and final disposal in the landfills of the municipalities investigated. In this study, real practical solutions were proposed for the specific reality of the municipalities so that they can have autonomy and decision-making power over the processes involved with the management of household solid waste.

According to the FIPE (2017) report on the economic and financial aspects of the implementation, operation, and closure of landfills, the reduction of costs in larger enterprises enables the transport of waste over greater distances. In this regard, the regionalization of landfills can be a cost-saving measure. The results of this study determined a value of R$ 156.83 per ton for the final disposal of waste in landfills with a capacity to receive 300 tons every day. Naruo (2003) analyzed the implementation and operation of landfills for small municipalities and found the adjusted average value for 2017 of 114.74 R $/ton for final waste disposal in the state of São Paulo.

According to the SNIS report for 2015 (MCIDADES 2017), the expenses of the handling of solid waste (minus the costs of regular collection) were 72.46 R$/inhab./y in Ipeúna, 52.31 R$/inhab./y in Rio Claro, and 66.82 R$/inhab./y in Santa Gertrudes. These values also include other services that were not included in this research, such as selective collection, pruning and weeding services, and cleaning public places. The values found in this research included the treatment and final disposal stage, and the treatment of waste could influence the values

The SNIS report for 2016 (MCidades 2018) reported that the average expense of the management of urban solid waste for the Southeast region was 136.28 R$/inhab./y, and it was 121.62 R$/inhab./y for Brazil. The ABRELP (2017) report states that Brazilian municipalities spent an average of 124.00 R$/inhab./y on waste management. This amount includes expenses from regular collection, selective collection, pruning, weeding, urban cleaning services, transportation, and final disposal. In the municipalities studied, an average of 45% of the total spent on waste management is related to regular collection.

The values presented in this study referred to the stage of final disposal and treatment of organic waste, and therefore represent estimates of values to compare different waste management alternatives. Thus, solutions were sought to manage urban solid waste in a more intelligent and appropriate way through available technologies and their practical application. This study aimed to contribute information on handling the waste of small cities with simple action techniques and technology available in the market to allow appropriate management of the different types of material so that the resources present in the waste can be circulated in the market. However, further studies are needed to analyze and assess the positive impacts of carrying out the treatment of organic waste with recovery of compost and energy.

To implement practical solutions, there must be a form of charging for waste management services. In this sense, the existence of socially accepted tariff structures and effective collection mechanisms are key aspects for ensuring the financial sustainability of the system (GIZ 2015). The implementation of economic instruments capable of achieving sustainability for waste management systems is necessary. For this to occur, waste management must be a political priority so that sufficient resources are allocated by the responsible departments. Additionally, workers in waste management must be adequately trained, and the population must be intensely educated and aware so that there is participation in the segregation of materials (Nahman and Godfrey 2010). In this way, this work contributes information about possibilities and values so that the residues can be sent for treatment and final disposal.

CONCLUSIONS

1. The scenario of treatment of organic products by decentralized composting showed the highest values per inhabitant for all municipalities but the lowest values per ton, except for the smallest municipalities of Analândia and Corumbataí. More studies are needed to investigate alternative solutions, especially for small municipalities, as these have specific realities that can be used in different ways to deal with solid waste management and also find a source of income for the municipality.
2. The scenarios of organic treatment by centralized composting and biomethanization presented similar values per inhabitant. However, the anaerobic digestion scenario had somewhat lower average values. This suggests that solutions that go beyond simple landfill can be a source of income for municipalities that are able to make the transition to technologies with recovery of inputs and energy.
3. The biomethanization scenario included the commercialization of electricity, so it generated revenues that decreased costs. This cost reduction was especially notable in the last years of the project when the goals of diversion of organic waste through selective collection were higher.
4. The results indicated that the biomethanization scenario would surpass the composting scenario in the long term. However, the composting scenario did not consider the commercialization of the compost generated in the process.
5. The centralized composting scenario had lower values per ton for most municipalities, except Santa Gertrudes and Ipeúna,
6. Corumbataí presented high average values per ton for the scenarios, and these values were influenced by the low values of the generation data for this municipality.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education, Youth, and Sports [Operational Program Research, Development and Education] (Grant No. CZ.02.1.01/0.0/0.0/16_019/0000803 EVA4.0).

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Article submitted: March 25, 2021; Peer review completed: June 13, 2021; Revised version received and accepted: June 22, 2021; Published: June 23, 2021.
DOI: 10.15376/biores.16.3.5601-5617