

# REVISTA AIDIS

de Ingeniería y Ciencias Ambientales:  
Investigación, desarrollo y práctica.

## ECONOMIC ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT IN MIDSIZED METROPOLITAN AREAS OF BRAZIL

\* José Carlos Martins Ramalho <sup>1</sup>  
João Luiz Calmon <sup>1</sup>  
Diogo Appel Colvero <sup>2</sup>

*Recibido el 14 de mayo de 2023. Aceptado el 15 de agosto de 2023*

### Abstract

This paper addresses the incipient number of studies regarding municipal solid waste management in Brazil, where the federal law requires the inclusion of waste pickers in waste management and proposes waste diversion targets far from being attained. Therefore, decision-makers can make the best choice economically among alternative technological roadmaps that meet the legal requirements. The proposed alternatives combine biowaste treatments (open composting, closed composting, anaerobic digestion), recycling and final disposal methods (landfill and incineration) for a metropolitan region with two million inhabitants. The results show that incineration can lower the costs for the citizens, and the cost increase is modest if anaerobic digestion is chosen if no profit is intended after 20 years (IRR=0%). However, higher profit (8% and 16% IRR) causes a significant increase in the service fees, which could encourage the use of composting facilities with lower environmental performance. Furthermore, the high waste diversions scenarios have lower service fees than the low diversions counterparts because of the increase in revenue from sales of recyclable materials and employing 5,697 instead of 2,138 pickers to work at sorting facilities, therefore highly recommended.

**Keywords:** economic assessment, biodegradable waste, recyclable waste, commingled waste, developing countries.

<sup>1</sup> Programa de Pós-Graduação em Engenharia Ambiental, Universidade Federal do Espírito Santo, Brasil.

<sup>2</sup> Departamento de Engenharia Mecânica, Universidade Federal de Goiás, Brasil.

\* *Autor correspondente:* Programa de Pós-Graduação em Engenharia Ambiental, Universidade Federal do Espírito Santo, Av. Fernando Ferrari, 514, Vitória, Espírito Santo. CEP.: 29075-910, Brasil. Email: [jc\\_ramalho@hotmail.com](mailto:jc_ramalho@hotmail.com)

## Introduction

Sustainability, which makes existence bearable, viable, and equitable (Bialostocka, 2021), is threatened. The United Nations (2023) warned about the grim consequences of climate change, the global economic crisis and tensions between the Global North and South in the latest World Economic Forum in Davos. To change this scenario, the Sustainable Development Goals (UN, 2015) include zero hunger, decent work and economic growth, reduced inequalities, sustainable cities and communities, and climate action, issues that can be addressed with municipal solid waste (MSW) management.

In this sense, Barbosa *et al.* (2021) mention that although Brazil has made remarkable progress in environmental laws in the last 50 years, some of this progress has been dismantled with medium to long-term consequences. One of these regressions was the proposed waste diversion targets from landfills (MMA - Brazilian Ministry of the Environment, 2012), which are now very unambitious (MMA, 2020). Like Colombia, Brazil is one of the few countries with policies regulating waste picker integration in the MSW management systems (Calderón Márquez *et al.*, 2021). This can create formal jobs that can include pickers in material recovery facilities (MRFs) (Vesere *et al.*, 2021), even if the literature reports difficulties in formalizing enough pickers due to competition of mechanized facilities (Marello and Helwege, 2018).

A literature review of economic assessments of MSW management systems was performed to understand the state of research in this area. While most authors associated the economic analyses and life cycle costings with environmental life cycle assessments (LCA) or social LCA in their studies (Nubi *et al.*, 2022a, 2021) approached the economic and social sustainability pillars separately and then joined them in a multicriterial study (Nubi *et al.*, 2022b). This has the advantage of allowing for more complete conclusions from a broader point of view while allowing a thorough assessment of each component. Another observation is that more developing countries are producing literature on this subject, although it is still incipient in South America. In this continent, countries like Brazil have critical areas in which waste is improperly disposed of or, if this issue is already sorted, there is still insufficient recycling and biowaste treatment to meet landfill diversion targets, like in the Great Vitória Metropolitan Region, or GVMR (ES - Espírito Santo, 2019). Finally, economic analyses are decision-making tools that need to be carried out for specific geographic locations because they have to consider the individual characteristics of each studied area. Therefore, the conclusions of a study may vary if the methodology is replicated in a new location.

To address this research gap, the present study was performed in Brazil, a vast country with heterogeneous structural development, where the legislation obliges the inclusion of waste pickers in waste management (Brazil, 2010) and waste diversion targets were proposed by the Brazilian Environment Ministry (MMA, 2012; 2020), but are far from being attained (Colvero *et al.*, 2020;

Ramalho *et al.*, 2021). Great Vitória Metropolitan Region (GVMR), located in southeast Brazil, is mid-sized, densely populated and has seven municipalities, one of them touristic. Even though this region has eradicated dumps and its MSW management has made remarkable progress, with proper landfilling and energetic recovery, the amount of biowaste treatment and recycling is still incipient. The main goal of this study is to conduct an economic assessment of different technologic roadmaps. For these reasons, this study is important to assist decision-makers in choosing the best strategy to improve the general sustainability of MSW management in this region. This way, it can be a model to help other regions achieve an economically viable system to decrease the environmental impacts of MSW, also generating formal jobs that include people in society.

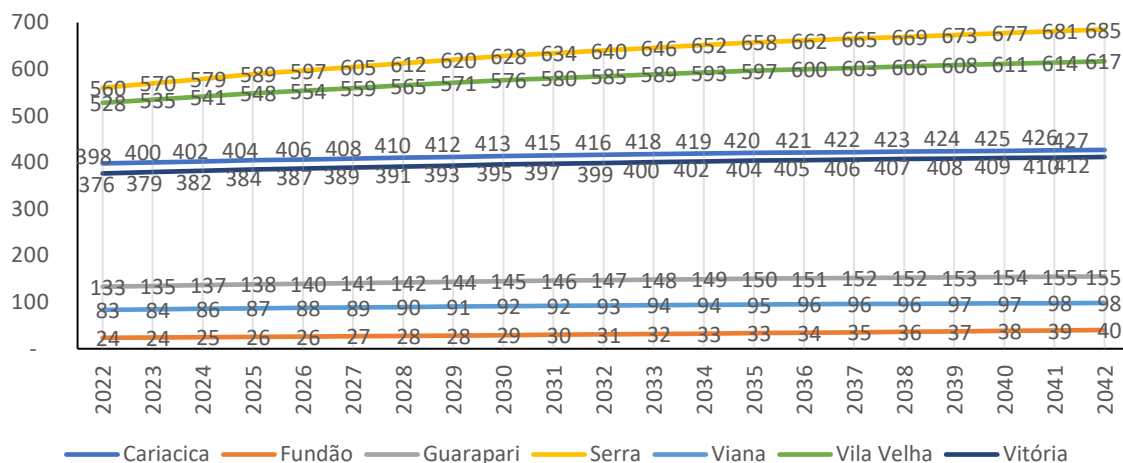
### Materials and methods

This economic assessment is comprised of three main phases. The first is the collection of necessary data, namely population, MSW generation, characterization and flows for the baseline and proposed scenarios, in the various municipalities that comprise the studied region. The second phase involves computing the costs and revenues, converting the currency to US dollars and extrapolating them to the correct year. The last step is to use economic assessment tools, like Net Present Value (NPV), Internal Rate of Return (IRR) and payback, to enable a discussion of the proposed MSW management options. Additionally, the number of pickers that can be included in Materials Recovery Facilities (MRFs) was calculated.

The Goal of this economic assessment is to propose different alternatives to the *status quo* in GVMR regarding MSW management, where only 0.82% are recycled and 0.75% are composted (Ramalho *et al.*, 2021). The proposed alternative is to attain the Brazilian Solid Waste Plan diversion targets, both high and low. The Scope of this paper is the management of domestic and public waste (that qualifies as MSW) generated yearly in GVMR, from collection to treatments and disposal in the landfill.

### Population, Waste Quantities and Characterization

The population of the seven GVMR municipalities between 2022-2040 is a projection from the Solid Waste State Plan (ES, 2019) and is presented in Figure 1 and Supplementary Material (SM) Table 1. However, since the time horizon is between 2022 (installation year) and 2042 (the 20<sup>th</sup> year of operation), the population for the last two years had to be calculated. To do so, the mean quotient of 2038, 2039 and 2040 (shown in SM Table 2) was used to estimate the population growth for 2041 and 2042. The rural municipality of Fundão was excluded because it has a sparse population, as seen in Figure 1, and its low amount of waste is sent outside GVMR.



**Figure 1.** Estimated population (in thousand inhabitants) of Great Vitória Metropolitan Region municipalities for the entire time horizon of the MSW management systems. *Note: Fundão is sparsely populated, therefore, was excluded from the assessment. Source: Adapted from ES (2019).*

As for the waste quantities, the average per capita values of commingled and source-separated recyclable collection in the latest years from the Brazilian Information System on Sanitation (SNIS) were calculated (Table 1). This was done to account for possible data uncertainties because the values of collected waste can vary and not necessarily follow the trend in all years. For all municipalities except Guarapari, the values used were from the years between 2016-2020 (SNIS, 2022), whereas for Guarapari, the newest available values were from between 2013-2017 (SNIS, 2022). This is because some municipalities do not promptly communicate their waste management information to SNIS. The population covered by the collection service, also from the same source, allowed to estimate the uncollected generated waste.

**Table 1.** Estimated per capita collection for the municipalities of Great Vitória Metropolitan Region.

	Collection coverage (%)	MSW collection	Total generation	SSC recyclables	SSC biowaste
			(t·inhabitant <sup>-1</sup> ·year <sup>-1</sup> )		
Cariacica	99.24	0.29	0.29	0.0023	0.0028
Guarapari	94.00	0.37	0.40	0.0033	n.i.
Serra	99.66	0.25	0.25	0.0009	0.0011
Viana	91.74	0.19	0.21	0.0022	0.0027
Vila Velha	99.17	0.35	0.36	0.0011	n.i.
Vitória	100.00	0.43	0.43	0.0074	0.0090
<b>Total %:</b>		<b>97.40%</b>	<b>100.00%</b>	<b>0.772%</b>	<b>0.700%</b>

*Legend: SSC – Source-separated collection; n.i. – not informed. Note: the percentages below refer to a fraction of the total amount of generated waste and estimations point to 1.128% of uncollected waste. Source: Adapted from SNIS (2022).*

As for source-separated biowaste not existent on SNIS, the composting facility in Cariacica reported a total amount of 5,193.23 t (Marca Ambiental, 2021) in 2020. It receives waste from Cariacica, Serra, Viana and Vitória. With this value and the amount of source-separated recyclables of these municipalities, it was possible to estimate the distribution of source-separated biowaste by each municipality and add it to the total generation, which is further described in the SM. With all estimated per capita values and population, the yearly MSW generation of each municipality was obtained for the entire time horizon (SM Table 4).

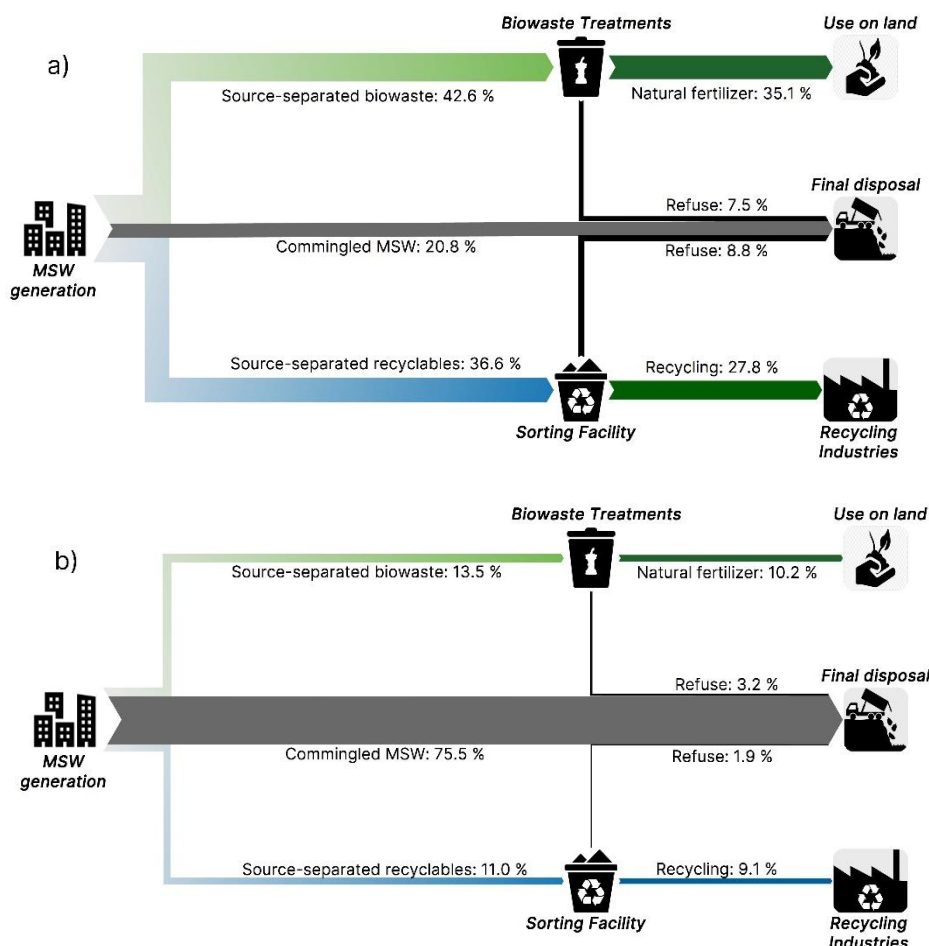
The characterization of the MSW generated in GVMR is the same as used in Ramalho *et al.* (2021), where the methodology used to obtain it is explained. SM Table 5 shows the composition of the undifferentiated, organic and recyclable waste, representing almost 43% of the total waste in this area. This fraction is approximately the same as vegetable waste, the most representative waste subfraction. Waste like multilayered packaging, comprised of layers of recyclable materials and Styrofoam, were included in the undifferentiated category because they are unfeasibly difficult or uneconomical to recycle.

### *Waste flows*

It is necessary to know the composition and how the yearly amount of generated/collected waste divides into flows to determine how much waste is sent to treatments (biowaste and recycling) or disposal. This information will be used to calculate all costs and revenues for the economic assessment. To do that, two main factors must be considered: the recyclable and biowaste diversion targets, which specify how much has to be effectively treated; and the treatment efficiencies, which define how much extra waste has to be sent to the treatments to account for the refuse that has to be disposed.

Regarding the two sets of targets, the high target is 70% for both recyclable and biowaste, which is the optimistic 2015 target for southeast Brazil proposed by the Brazilian Environment Ministry (MMA - Ministério do Meio Ambiente, 2012), while 25.8% for recyclables and 18.1% for biowaste (MMA, 2020) are the low targets that have superseded the previous ones. Note that both preliminary proposals are unapproved to the date of this study and the newer one has retracted the diversion targets (SM Table 6). Therefore, they were chosen to understand the impact of decreasing landfill diversions from an economic perspective. As for the efficiencies, 75% and 82.4% were assumed for MRFs and biowaste treatments, respectively, as in Ramalho *et al.* (2021). The result of this flow division is shown in Figure 2.

The two sets of targets combined with the different technologic roadmaps produced 12 scenarios. Each target has three scenarios with landfills and three with incineration. And each of these three scenarios uses one of these biowaste treatments: open or windrow composting, closed or tunnel composting and AD (Table 2). All scenarios have recycling, collection, transport and transfer stations (TSs), where their amount depends on the respective diversion targets.



**Figure 2.** Waste flows with diversion targets proposed in: a) 2012 – 70% of biowaste and recyclables (high), b) 2020 – 18.1% of biowaste, 25% of recyclables (low).

**Table 2.** Summary of the scenarios proposed for the Great Vitória Metropolitan Region

	High Diversions (70% biowaste/recyclables)	Low Diversions (18% biowaste/25% recyclables)
Final disposal:		
Landfill (LDF)	OC+LDF	OC+LDF
	CC+LDF	CC+LDF
	AD+LDF	AD+LDF
Incineration (WtE)	OC+WtE	OC+WtE
	CC+WtE	CC+WtE
	AD+WtE	AD+WtE

Note: All scenarios include Recycling. Legend: OC – Open Composting, CC – Closed Composting, AD – Anaerobic Digestion, LDF - Landfill, WtE – Incineration.

### Economic Assessment

With the waste amounts determined for all scenarios, the economic assessment can be initiated since costs and revenues are a function of the amount of waste to be treated. The capital expenditures or investment costs (CAPEX) occur in the zero-year of the system, 2022, while the operating costs or expenditures (OPEX) are calculated for every year of operation between 2023-2042. This is because the Brazilian Solid Waste Policy (Brazil, 2007) requires that the MSW management systems are designed for periods of 20 years. Similarly, some facilities generate revenues with sales, as is the case of material recovery facilities (MRF), AD, composting and incineration (WtE).

Because the currency chosen for this study is US Dollar (US\$), the monetary values in Euros (€) or Brazilian Reals (R\$) needed to be converted into this currency. The used conversion factors of 1.00€ = US\$1.1369 and R\$1.00 = US\$0.2176 were the mean exchange rates of the last five years shown in SM Table 7 (BCB - Brazilian Central Bank, 2022a; ECB, 2022). This step was done to reduce the effects of currency volatility. And since the costs and revenues of the different facilities system are from different sources and years, they needed to be updated to the implementation year of the system (Colvero *et al.*, 2020; Soares *et al.*, 2015), in this case 2022, using Equation 1:

$$V_f = V_p \cdot (1 + i)^y$$

Equation (1)

Where:  $V_f$  is the future value,  $V_p$  is the present value,  $i$  is the yearly interest rate, and  $y$  is the number of years between  $V_f$  and  $V_p$ .

Regarding the  $i$ -value, the mean value ( $i=5.118\%$ ) of the interest rates between December 2017 (minimum 2.95%) and December 2021 (maximum 10.06%), shown in SM Table 8 (BCB, 2022b), was used to update the calculated yearly values between 2023-2042 to the current operation year, as well as the unit costs and revenues.

### Logistics costs

Waste logistics involves (1) waste collection service for all municipalities; (2) transfer stations (TSs) in municipalities where waste has to be sent to a distance greater than 25 km (Ferronato *et al.*, 2022); and (3) transport from the TSs to the landfills, using 25-ton trucks (Vergara *et al.*, 2016). This transport component can be either direct or indirect, as in most municipalities, where their waste is gathered at TSs before being sent to landfills. Instead, Viana and Cariacica transport their waste directly to the treatment and disposal facilities in Cariacica, located less than 25 km from the town centers. Therefore, the OPEX for the logistic facilities is presented in Table 3, while the CAPEX was omitted from the calculations, as the facilities are already in operation.

Because the transport costs are a distance function, the distances used to calculate the OPEX from Figure 3 must be multiplied by the transport distances between TSs and landfills (SM

Table 9). It is noteworthy that the TSs are correctly located less than 25 km from waste generation in all municipalities of GVMR.

### *Recycling*

As each municipality currently has at least one waste picker organization, the costs and revenues with the sale of recyclables were calculated for each municipality. This is because decentralizing MRFs is a sustainable practice that lowers transport costs and environmental impacts while bringing income to the municipalities and local population (Colvero *et al.*, 2019). To calculate the CAPEX, OPEX and revenues for all scenarios, the values from Table 3 were used in conjunction with the estimated waste quantities from *Population, Waste Quantities and Characterization* section. Since the current facilities operated by waste pickers cannot process the waste quantity needed to attain any proposed diversion target, new investments have to be made in MRFs.

In addition to the costs of MRFs, which depend on whether they are mechanized or not, they also create jobs. To estimate the number of workers necessary to operate the MRFs, it is necessary to know if the amount of waste that arrives at the MRF is under or over the 15 t·day<sup>-1</sup> limit. This value is generally exceeded in all municipalities in all scenarios, with a single exception: the municipality of Viana does not reach nine daily metric tons in low diversions scenarios. For that single case, manual MRFs with a productivity rate is 2-2.5 t·person<sup>-1</sup>·month<sup>-1</sup> were assumed (Colvero *et al.*, 2016); for all other scenarios with mechanized MRFs, a productivity rate is 3.5-4 t·person<sup>-1</sup>·month<sup>-1</sup>. Notably, the Brazilian Solid Waste Policy (Brazil, 2010) prioritizes Federal funds for MSW management to the municipalities that hire waste pickers in MRFs.

### *Organic Treatments and Final Disposal*

The CAPEX and OPEX must be calculated for biowaste treatments and incineration, while OPEX suffices for the existing landfills in GVMR. The CAPEX also had to be calculated if the studied area needed new landfills. Because the cost functions in Table 3 were used, the unit cost must be calculated with the waste quantity to be multiplied again by the amount of waste to obtain the total cost for each facility. For the landfills, the total costs are calculated directly with the primary unit value (Table 3). Finally, Euros and Reais values were converted to Dollars, as explained above.

It is worth mentioning that the functions to calculate the CAPEX and the OPEX have applicability limits. To ensure these limits in low diversion scenarios, the amount of waste was combined into two groups: the municipalities that sent their waste to Cariacica (Cariacica, Serra, Viana and Vitória) and the ones that send to Vila Velha (Vila Velha and Guarapari). This split implies that there will be only one large composting, AD or incineration facility for each group, located beside the current landfills. Contrarily, for the high diversions scenarios, the amount of biowaste to be treated is enough to calculate the costs of individual biowaste facilities. However, the same group arrangement is maintained for incineration facilities, as they require large amounts of waste to be feasible.

Notably, the actual placement of the facilities in the municipalities must observe specific legal criteria that have to be studied separately with specific geoprocessing tools, as performed by Colvero *et al.* (2018). Therefore, some facilities may be reassigned to the municipalities, causing variations to the CAPEX, OPEX and transport distances, thus changing the service fees to the inhabitants.

**Table 3.** Unit capital and operational expenses (CAPEX and OPEX) and Revenues for the Great Vitória Metropolitan Region facilities

		OPEX	
		2022 (US\$·t <sup>-1</sup> )	
<b>Collection - Reichert (2013)</b>			
Source-separated recyclables		65.42	
Source-separated biowaste		60.13	
Commingled collection		31.92	
<b>Transport – Bezerra (2012)</b>		<b>2022 (US\$·t<sup>-1</sup>·km<sup>-1</sup>)</b>	
Indirect (Guarapari, Serra, Vitória, Vila Velha)		0.08	
Direct (Viana, Cariacica)		0.12	
<b>Transfer Stations – Pereira (2013)</b>		2022 (US\$·t <sup>-1</sup> )	
		7.06	
<b>Materials Recovery Facilities – BNDES (2014)</b>			
Population (10 <sup>3</sup> inhabitants)		CAPEX 2022 (US\$·t <sup>-1</sup> )	OPEX 2022 (US\$·t <sup>-1</sup> )
<10		10.70	158.29
10-30		5.35	147.58
30-250		5.84	160.56
250-1,000		3.73	48.92
>1,000		2.27	22.70
Material		REVENUE 2022 (US\$·t <sup>-1</sup> )	
Paper		61.63	
Plastic		133.95	
Ferrous metal		58.38	
Non-ferrous metal		784.13	
Glass		25.95	
<b>Tsillemou &amp; Panagiotakopoulos (2006)</b>			
	Waste amount (10 <sup>3</sup> t·year <sup>-1</sup> )	CAPEX 2006 (€·t <sup>-1</sup> )	OPEX 2006 (€·t <sup>-1</sup> )
Open Composting	(2≤x≤100)	4,000·x <sup>0.7</sup>	7,000·x <sup>-0.6</sup>
Closed Composting	(2≤x≤120)	2,000·x <sup>0.8</sup>	2,000·x <sup>-0.5</sup>
Anaerobic Digestion (AD)	(2.5≤x≤100)	35,000·x <sup>0.6</sup>	17,000·x <sup>-0.6</sup>
Incineration	(20≤x≤100)	5,000·x <sup>0.8</sup>	700·x <sup>0.3</sup>
<b>Marca Ambiental (2022)</b>			
		OPEX 2022 (US\$·t <sup>-1</sup> )	REVENUE 2022 (US\$·unit <sup>-1</sup> )
<b>Landfill</b>			
Compost/Digestate (t) – Composting/AD		26.11	60.92
Energy from biogas (MWh) – AD			102.26
Energy from incineration (MWh) – WtE (ABRELPE, 2013)			117.53

Regarding revenue, composting facilities generate income from compost sales. AD sells both stabilized digestate (assuming the same price as compost) and electricity from biogas, while incineration produces electricity. The average yield of composting facilities is 35% (Marca Ambiental, 2021), whereas the digestate yield for AD was 14.1% (Clavreul *et al.*, 2014). To determine how much energy is produced by AD and incineration, Equations 2 and 3 adapted from Fernández-González *et al.* (2017) were used, respectively:

$$E_{AD} = (0.28 \cdot W_{biow} \cdot LHV_{AD} \cdot R \cdot \eta_{AD}) / 1000 \quad \text{Equation (2)}$$

$$E_{WtE} = (0.28 \cdot W_{cmgl} \cdot LHV_{WtE} \cdot \eta_{WtE}) / 1000 \quad \text{Equation (3)}$$

Where:  $E$  is the amount of energy produced in MW·h;  $0.28$  is the conversion factor from MJ to kW·h;  $W$  is the yearly biodegradable or commingled waste input in metric tons;  $LHV$  is the lower heating value of methane or the waste input in incineration, as detailed below;  $R$  is the ratio of methane generation per metric ton of biowaste:  $115 \text{ Nm}^3 \cdot \text{t}^{-1}$  (Fernández-González *et al.*, 2017);  $\eta$  is the efficiency of the facilities: 29% was assumed for AD (Fernández-González *et al.*, 2017) and 22% for incineration (Brogaard and Christensen, 2016), as in the Brazilian study by Colvero *et al.* (2020).

For the  $LHV$  values,  $37.2 \text{ MJ} \cdot \text{Nm}^{-3}$  (Fernández-González *et al.*, 2017) was adopted for AD, while for incineration, the life cycle assessment software EASETECH (Clavreul *et al.*, 2014), together with the waste flows of Figure 2 and the MSW characterization for GVMR (Ramalho *et al.*, 2021) were used. The lower heating values of the waste mix arriving at the incineration are  $10,504 \text{ MJ} \cdot \text{t}^{-1}$  and  $9,405 \text{ MJ} \cdot \text{t}^{-1}$  for the high and low diversions scenarios, respectively. The yearly revenues from these facilities were calculated with the amount of energy calculated with Equations 2 and 3 and the unit values indicated in Table 3 for biogas and incineration energy.

### Economic feasibility assessment and service fees

Having all yearly costs and revenues calculated, it is quickly understood that the gains from sales alone are insufficient to cover the expenses. And because the Brazilian law no. 11,445/2007 (Brazil, 2007) determines that the economic feasibility of the MSW management system must be guaranteed and its beneficiaries can be charged a fee to cover operation and maintenance costs. As in Colvero *et al.* (2020), this study assumes that the investments can either be made by the State or shared with the private sector through a public-private partnership. This section will explain the calculations behind the service fees that ensure the project is paid by the end of the 20-year time horizon or earlier.

To calculate the service fees, the Operation Results are found by subtracting the yearly costs from the yearly revenues (facility revenues and service fee). Then the Exploration Cashflow and Investment Cashflow are calculated as in Colvero *et al.* (2020) and summed to obtain the Global Cashflow. This cash flow is extrapolated to the present value using Equation 1 to calculate the Present Value. Therefore, the total annual service tax equals the total yearly OPEX multiplied by

a factor ( $\Phi$ ), which will be the dependent variable that changes with the desired conditions of the economic assessment, the independent variable. For instance, if  $\Phi=1$ , the total collected service fees are equal to the OPEX in all years. To determine the actual  $\Phi$ , the Solver tool of Microsoft Excel was used so that the net present value (NPV) is zero in the 0% IRR. This is a social scenario where the public investment in 2022 will be completely paid by the end of 2042, without profit or debt, run by the local government and providing the lowest fees for the population.

Additionally, two profit-oriented alternatives were analyzed, with 8% and 16% IRR values. The first, 8% IIR, as used by Colvero *et al.* (2020), is comparable with other studies (Khan *et al.*, 2016; Lombardi and Francini, 2020; Luz *et al.*, 2015) and would guarantee profitability to potential investors. But because of the high variability of inflation in Brazil, which has surpassed 10% in 2021 (IBGE, 2023), the 16% IRR was also tested to understand how a profitable MSW management system in a high inflation scenario would impact the service fees. This value aligns with the 15.6% IRR proposed in the technical document by the Brazilian Institute for Applied Economic Research (Rocha *et al.*, 2012) and other studies (Aracil *et al.*, 2018; Mabalane *et al.*, 2021). For higher-risk scenarios and novel technologies, the IRR targeted by the literature was as high as 20% (Copa *et al.*, 2020) or 25% (Yang *et al.*, 2018).

With the multiplication factor  $\Phi$  known for every scenario and IIR, the total service fees obtained must be divided by all municipalities. So, the individual costs were added to the shared costs. The shared facilities are the landfills, incineration and biowaste treatments (only in the LOW diversions scenarios). In this case, the total OPEX of the shared facility was divided by the amount of commingled or biodegradable waste sent there by a municipality over the sum of waste sent by all municipalities of GVMR that share that facility. On the other hand, since the OPEX of waste collection and transport, MRFs and biowaste facilities (in the HIGH diversion scenarios only) are individual, the values per municipality are already known.

## Results and discussion

### Feasibility assessment and service fees

The results of this economic assessment (Table 4) show that the proposed MSW management system can be financially viable, i.e., it will be paid by the end of the project (20-years payback time, zero NPV), with modest service fees (monthly cost of US\$4 per capita maximum), especially if the system is not aimed at profit (Figure 3 – IIR=0%). However, if a profit is intended through increasing service fees, the payback time will be sooner than the 20-year time horizon. So, with an 8% IRR, the payback time will be during the 10<sup>th</sup> and 11<sup>th</sup> years, as in Lin *et al.* (2019), and sooner for the 16% IRR, during the 7<sup>th</sup> year, depending on which technological roadmap is chosen. Since the current MSW management system in GVMR has the participation of private entities, further considerations on the 8% and 16% IIR must be made.

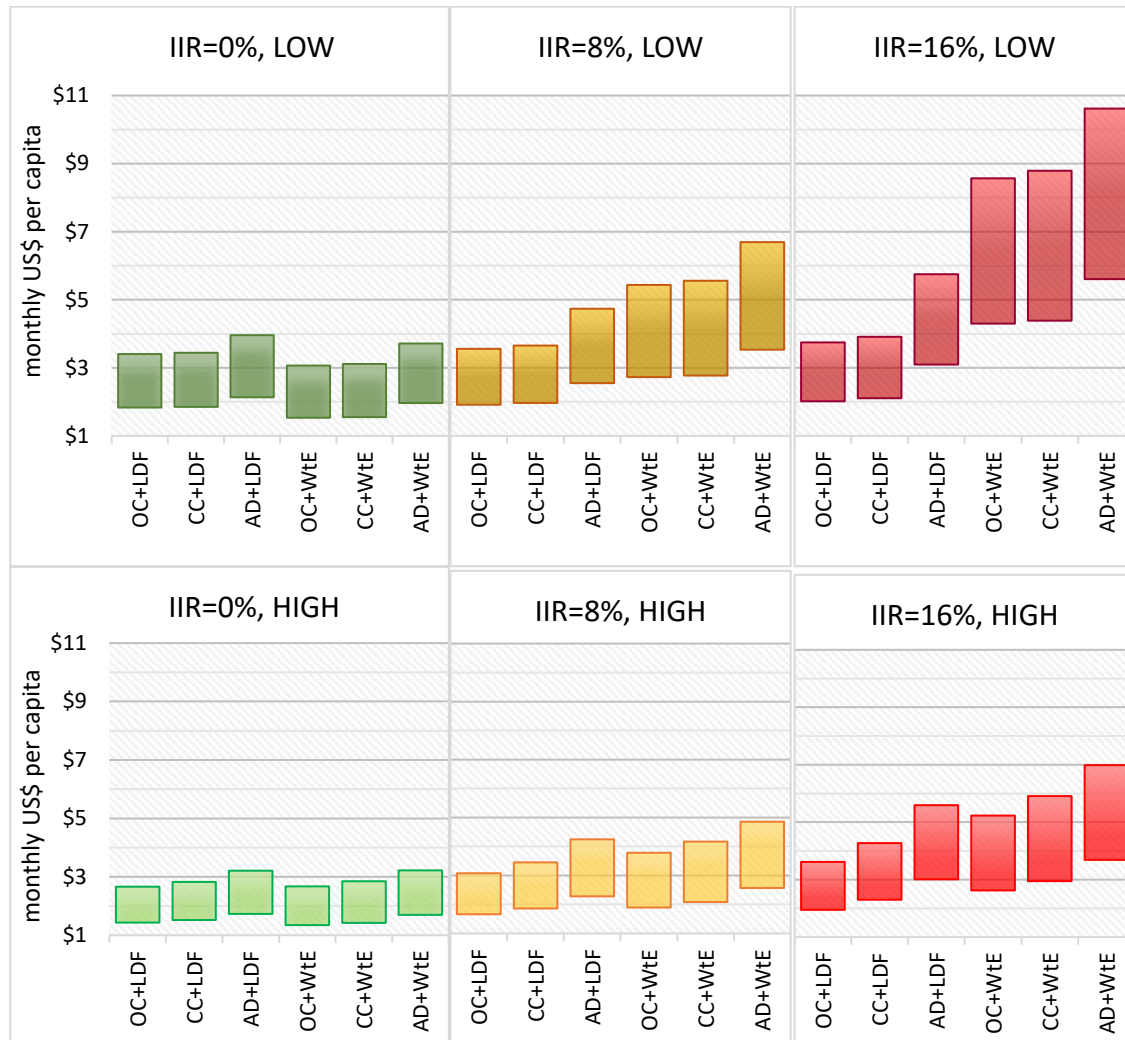
**Table 4.** Net present value (US\$) and payback time (years) of the facilities and scenarios proposed for the Great Vitória Metropolitan Region

Scenarios:	IRR: 0%		8%		16%	
	NPV (US\$)	Payback (years)	NPV (US\$)	Payback (years)	NPV (US\$)	Payback (years)
<b>HIGH diversions:</b>						
OC+LDF	0	20.0	131,740,847	11.9	303,880,420	7.2
CC+LDF	0	20.0	195,756,252	11.9	452,253,452	7.2
AD+LDF	0	20.0	377,343,519	12.0	871,223,492	7.2
OC+WtE	0	20.0	354,647,238	12.0	819,226,687	7.2
CC+WtE	0	20.0	418,683,815	12.0	886,362,913	7.2
AD+WtE	0	20.0	590,253,575	12.0	1,493,493,479	7.2
<b>LOW diversions:</b>						
OC+LDF	0	20.0	50,182,922	12.7	84,796,381	7.2
CC+LDF	0	20.0	67,046,398	12.0	124,076,944	7.4
AD+LDF	0	20.0	266,678,234	11.7	614,829,373	7.8
OC+WtE	0	20.0	673,745,488	11.9	1,563,448,595	7.9
CC+WtE	0	20.0	690,625,011	11.9	1,602,917,379	7.9
AD+WtE	0	20.0	888,712,302	11.9	2,061,547,443	7.9

Legend: OC – Open Composting, CC – Closed Composting, AD – Anaerobic Digestion, LDF – Landfill, WtE – Incineration, NPV – Net Present Value.

The monthly service fees to be charged to the population are shown in Table 3, which are also presented for each municipality in SM Table 11, on a weight basis, and SM Table 12 every year. These fees are directly related to the CAPEX, OPEX and revenues of each individual facility, with are further discussed in the SM and presented in SM Table 10. So, for systems aimed at profit, it is visible in Figure 3 that abiding by the proposed diversion targets while insisting on the current technology (composting and landfilling) has modest increases in the service taxes (less than one dollar per month per inhabitant) when compared to a socially aimed, but economically feasible project (0% IIR). However, it is consensual that composting has poorer environmental performance than the more expensive AD (Lin *et al.*, 2018).

On the other hand, the scenarios with incineration are less expensive for the service payers than the ones with landfills on the social IIR, and the exact opposite happens when profit is aimed. This has to do with the investment costs, which are high for incineration and none for the already existent landfills. This result is consistent with Sharma and Chandel (2021), even though the landfill CAPEX was included. So, despite the higher potential revenues of the incineration, the increased investment has to be paid for sooner for the system to be profitable, resulting in nearly duplicating (8% LOW) or triplicating (16% LOW) the cost for the users. This is where increasing the diversions becomes economically attractive. That fee gap is diminished for the HIGH scenarios, so from the 0-16% IIR, the fee rises 16-51% (depending on the technological roadmap) instead of increasing 38-117% in the LOW scenarios. This opens up the choice for scenario recommendations which will be further discussed.



**Figure 3.** Monthly service fee to be charged to each inhabitant for 0%, 8% and 16% internal rates of return (IRR), low and high diversion targets, and six proposed technological roadmaps. Note: the numeric values for each municipality are presented in Table 11 of the Supplementary Material. Legend: OC – Open Composting, CC – Closed Composting, AD – Anaerobic Digestion, LDF – Landfill, WtE – Incineration.

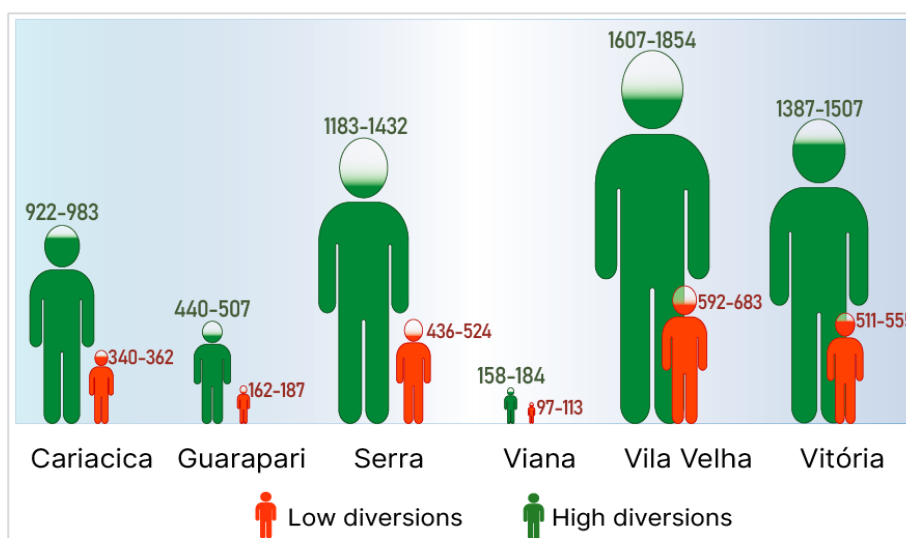
Since the fees are low in all scenarios with low variations for a project with no profit intended (0% IIR), the most recommended scenarios are those with AD since the environmental benefit is the best. Inclusively, the produced biogas could serve as a fuel to power the waste collection vehicles after upgrading to biomethane, potentially decreasing the logistics cost, almost half of all OPEX. Adding incineration to the system would further decrease the service fees because this facility generates much more revenue than landfills.

As for the profit-aimed scenarios, the recommendations change dramatically. For the low diversion targets, which are easier to achieve, the scenarios become expensive for the inhabitants as costly facilities are introduced (AD, WtE), even with the added revenue. Therefore, the recommendations go toward opting for the existing landfills instead of building new incineration facilities and CC instead of OC for an increase in environmental performance, with a small price increase, or even AD, with a further fee increase, but with major environmental benefits. As the IIR increases, incineration becomes less and less interesting for the high fees caused by the high investment cost associated with a higher profit and sooner payback.

But, for the high diversions scenarios, the fees increase less than in the low diversions scenarios, and due to the different distribution of waste through the flows, there are different considerations to be made. Because the incineration does not increase the price as much as before, the AD+LDF scenario is now slightly more expensive than the OC+WtE and the CC+WtE in the 8% IIR only. Still, the most expensive scenario in the 8% IIR is under 5 dollars for the most expensive municipality. Therefore, even though the scenario price order changes, their differences are smaller. So, choosing a technology with better environmental performance, like AD, does not add to the price when comparing the same scenario with HIGH diversion targets.

#### Potential jobs creation

Figure 4 shows the number of jobs, calculated as explained in section 2.2.2, which can be created at MRFs if the waste diversion targets are attained.



**Figure 4.** Number of pickers needed at the materials recovery facilities of Great Vitória Metropolitan Region for the two recyclable waste diversion targets, 70% (MMA, 2012) and 25% (MMA, 2020), for the first (minimum) and last (maximum) year of operation of the systems.

As presented, the more recyclable waste is diverted from landfills into the MRFs located in each municipality, the more workers are needed to sort the materials. And since the amount of waste to be treated increases during the 20 years of system operation, so does the number of workers at the recycling plants. Therefore, diverting waste from landfills has environmental and economic benefits and can open job opportunities, fostering social inclusion, so recycling is a sustainable practice. Notably, the municipalities of Vila Velha and Vitória can employ more pickers than Serra, which is more populous. This is because waste generation depends on socioeconomic factors like income (Ozcan *et al.*, 2016). Serra has more low-income inhabitants, which consume less, producing less waste.

### Conclusion

This conducted an economic assessment of different technologic roadmaps for MSW management in for GVMR seeks to comply with the proposed waste diversion targets while being financially sustainable, which is also a legal requirement. These solutions combine three biowaste treatment technologies, open composting, closed composting and anaerobic digestion with energy recovery from biogas, and two alternatives for final disposal, landfills and incineration with electricity generation. Moreover, two distinct sets of diversion targets were considered, the high targets proposed in 2012 and the low targets proposed in 2020. On top of that, the service fees that are fundamental to the financial sustainability of the system were calculated based on three internal rates of return, 0% for a social project, 8% for a project in a moderate inflation scenario and 16% in a high inflation, risky scenario.

Regarding the facilities that comprise the proposed MSW management system alternatives, collection is where the waste enters the system, unexpectedly roughly representing half the total costs in high diversion targets, with the most source-separated collection. This expense could be potentially decreased by using the generated biomethane to replace diesel used by the waste collection vehicles. However, it was not analyzed in this article due to the complexity of the assessment and lack of data. The second most expensive facility in terms of OPEX was AD, despite being the second one that generates the most revenue. As for the largest revenue generators in high diversions scenarios, MRFs sell recyclable materials to industries if there is demand. The situation is different in low diversions because landfills cost the most in operation, second by incineration, which generates much more revenue than the OPEX.

However, what matters is the economic performance of the scenarios, which combine different facilities and diversion targets, changing the conclusions. So, the scenarios with incineration had considerably more revenue than the scenarios with landfilling. However, the high CAPEX of incineration competes with zero investment in new landfills, as these facilities are already in operation in GVMR. Regarding service fees, incineration is less costly to the population if the low

diversion targets are met and the project is not profit-oriented (0% IRR). In this way, the high amount of energy generation pays for the high investment costs. Otherwise, if private enterprise seeks a profitable investment (payback much earlier than 20 years), the costs will undoubtedly rise for the citizens of GVMR.

Concerning the impact of biowaste treatments on the scenarios, the difference is negligible between both types of composting, irrespective of the IRR, but increases slightly with the diversions of biowaste. Differently, for the scenarios with AD, the fees increase significantly in higher IRRs, but ever so slightly with the increase in diversion targets. Comparing correspondent scenarios with different diversion targets, it is safe to assume that the more waste is diverted from landfills, the lesser the service fees paid by the population.

Beyond these economic considerations, achieving the highest diversion targets is the most sustainable option, as it benefits the environment and fosters the creation of a higher number of job opportunities for the pickers at the MRFs. In turn, this ultimately helps the local economy and includes people below the subsistence level in the economy. Therefore, a social project would allow for the choice of scenarios with a better environmental performance at a lower cost for the population while being economically feasible in 20 years. Conversely, if high profits are sought, the service fees are likely too expensive for high-tech options with potentially higher revenues, like AD or incineration.

This study considered that the biogas from AD was used to generate electricity, but it could also be used as a cooking fuel or upgraded to be used as a vehicular fuel. In this sense, a potential future study should make an economic comparison of these options, including the substitution of waste collection vehicles powered by biomethane instead of using diesel fuel. Another issue is that the cost functions used to estimate some costs of MSW management facilities are based on European facilities. Therefore we suggest conducting a similar study for South American or even Brazilian facilities to make more accurate estimations. Finally, studies conducted with geoprocessing tools could allow for further optimization of the collection routes and facility placement.

### **Acknowledgments**

*This study was partly financed by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (College and Graduate Education Improvement Coordination), Brazil (CAPES), Finance Code 001. The authors also acknowledge the financial support given by Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (Espírito Santo Research and Innovation Support Foundation – FAPES) project 107/2019, as well as Marca Ambiental for the provided data.*

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## Supplementary material

### Population data

The Solid Waste Plan for Espírito Santo State (ES, 2019) is a legal instrument that was produced for a 20-year time horizon (2020-2040), from where a population projection for the municipalities of Great Vitória Metropolitan Region (GVMR) was obtained (SM Table ). The time horizon for this study is also 20 years, but since the period starts two years later (2022-2042), the population values for the last two years are lacking. Therefore, they had to be estimated.

**SM Table 1.** Population in the municipalities of Great Vitória Metropolitan Region

	Cariacica	Guarapari	Serra	Viana	Vila Velha	Vitória
2022	397,720	133,277	560,133	83,328	527,780	376,161
2023	399,933	134,956	569,692	84,475	534,589	378,868
2024	402,167	136,651	579,342	85,634	541,464	381,601
2025	404,423	138,363	589,083	86,804	548,403	384,360
2026	406,210	139,718	596,803	87,731	553,902	386,546
2027	408,011	141,085	604,580	88,664	559,442	388,749
2028	409,825	142,461	612,415	89,605	565,023	390,968
2029	411,653	143,847	620,308	90,553	570,646	393,204
2030	413,494	145,244	628,261	91,508	576,311	395,456
2031	414,841	146,266	634,077	92,206	580,454	397,103
2032	416,195	147,293	639,924	92,908	584,620	398,759
2033	417,556	148,326	645,804	93,614	588,808	400,425
2034	418,925	149,364	651,715	94,324	593,019	402,099
2035	420,301	150,408	657,658	95,037	597,253	403,782
2036	421,199	151,089	661,535	95,503	600,014	404,880
2037	422,099	151,772	665,425	95,970	602,786	405,982
2038	423,003	152,458	669,329	96,439	605,567	407,087
2039	423,910	153,146	673,246	96,909	608,357	408,197
2040	424,821	153,836	677,178	97,381	611,158	409,310
2041	<i>425,732</i>	<i>154,530</i>	<i>681,142</i>	<i>97,856</i>	<i>613,974</i>	<i>410,425</i>
2042	<i>426,645</i>	<i>155,227</i>	<i>685,129</i>	<i>98,333</i>	<i>616,803</i>	<i>411,543</i>
Average	414,698	146,158	633,466	92,132	580,018	396,929

Adapted from: ES - Espírito Santo (2019). Note: the numbers in italic were estimated from the average population increase between 2037 and 2040, shown in SM Table 2.

To estimate the population values of the municipalities of GVMR, the population of the last four years was used to calculate the population growth and, consequentially, the mean population growth for these years (SM Table ). Then, assuming these mean values, estimating the population values for the years beyond 2040, i.e., 2041 and 2042 was possible.

**SM Table 2.** Population growth used to calculate the estimated population values for 2041 and 2042

Period	2037-38	2038-39	2039-40	Average
Cariacica	0.2142%	0.2144%	0.2149%	0.2145%
Guarapari	0.4520%	0.4513%	0.4506%	0.4513%
Serra	0.5867%	0.5852%	0.5840%	0.5853%
Viana	0.4887%	0.4874%	0.4871%	0.4877%
Vila Velha	0.4614%	0.4607%	0.4604%	0.4608%
Vitória	0.2722%	0.2727%	0.2727%	0.2725%

### Waste data

To estimate the amount of data generated in GVMR that will be managed every year between 2023 and 2042, the latest five per capita waste collection values were obtained from the Brazilian Sanitation Information System (SNIS, 2022) for commingled waste and recyclable waste for the municipalities of GVMR. Since not all municipal solid waste (MSW) produced is collected, because the MSW collection services do not cover a small percentage of the population, the collection coverage was used to determine how much waste is uncollected but generated. The average values of per capita MSW collection and the collection coverage are shown in Table 1 of the Manuscript (MS).

However, since there is no information regarding the source-separated collection of biowaste on SNIS, the values for each municipality had to be estimated. So, the 5,193.23 metric tons of biowaste that arrived at the composting facility in Cariacica (Marca Ambiental, 2022) in 2020 were split by the municipalities that send their waste to that facility (SM Table ). These values were estimated using the amount of source-separated recyclables collected from those municipalities, calculating the proportions and multiplying by the total biowaste value. This step allowed estimating the total amount of MSW per capita generated in the municipalities of GVMR analyzed (MS Table 1), which in turn enabled the calculation of the estimated yearly MSW amount to be treated between 2022 and 2042 (SM Table ).

**SM Table 3.** Estimation of source-separated biowaste collection for the Great Vitória Metropolitan Region municipalities

Municipality	Source-separated recyclables	Proportion %	Source-separated biowaste
	t		t
Cariacica	969.0	21%	1,113.14
Serra	454.0	10%	521.56
Viana	174.0	4%	199.88
Vitória	2,923.8	65%	3,358.65
Total	5,578.5	100%	*5,193.23

**SM Table 4.** Amount of municipal solid waste generated in the municipalities of the Great Vitória Metropolitan Region, for the period of the economic analysis

	Cariacica	Gurapari	Serra	Viana	Vila Velha	Vitória	Total
2020	129,807.2	19,494.9	178,623.7	9,727.7	169,736.5	122,371.3	632,213.0
2021	130,523.9	19,742.1	181,719.1	9,862.9	171,941.6	123,248.1	639,556.5
2022	131,247.6	19,991.6	184,843.9	9,999.4	174,167.4	124,133.1	646,970.5
2023	131,977.9	20,243.4	187,998.4	10,137.0	176,414.4	125,026.4	654,455.7
2024	132,715.1	20,497.7	191,182.9	10,276.1	178,683.1	125,928.3	662,014.0
2025	133,459.6	20,754.5	194,397.4	10,416.5	180,973.0	126,838.8	669,645.1
2026	134,049.3	20,957.7	196,945.0	10,527.7	182,787.7	127,560.2	675,709.6
2027	134,643.6	21,162.8	199,511.4	10,639.7	184,615.9	128,287.2	681,821.1
2028	135,242.3	21,369.2	202,097.0	10,752.6	186,457.6	129,019.4	687,979.5
2029	135,845.5	21,577.1	204,701.6	10,866.4	188,313.2	129,757.3	694,185.7
2030	136,453.0	21,786.6	207,326.1	10,981.0	190,182.6	130,500.5	700,439.7
2031	136,897.5	21,939.9	209,245.4	11,064.7	191,549.8	131,044.0	705,039.0
2032	137,344.4	22,094.0	211,174.9	11,149.0	192,924.6	131,590.5	709,664.9
2033	137,793.5	22,248.9	213,115.3	11,233.7	194,306.6	132,140.3	714,318.5
2034	138,245.3	22,404.6	215,066.0	11,318.9	195,696.3	132,692.7	718,998.8
2035	138,699.3	22,561.2	217,027.1	11,404.4	197,093.5	133,248.1	723,706.5
2036	138,995.7	22,663.4	218,306.6	11,460.4	198,004.6	133,610.4	726,814.1
2037	139,292.7	22,765.8	219,590.3	11,516.4	198,919.4	133,974.1	729,934.7
2038	139,591.0	22,868.7	220,878.6	11,572.7	199,837.1	134,338.7	733,068.8
2039	139,890.3	22,971.9	222,171.2	11,629.1	200,757.8	134,705.0	736,216.1
2040	140,190.9	23,075.4	223,468.7	11,685.7	201,682.1	135,072.3	739,377.7
2041	140,690.3	23,247.7	225,626.1	11,779.9	203,219.1	135,683.4	744,533.0
2042	141,053.3	23,372.9	227,193.7	11,848.4	204,335.8	136,127.4	748,318.3

As for the elements that constitute the waste generated in GVMR, the MSW characterization determined in a previous study of the same region (Ramalho *et al.*, 2021) was also applied in this economic analysis, as shown in (SM Table 5).

The proposed legal waste diversion targets from landfills, over which the waste flows of the MSW management system scenarios in MS Figure 2 were built, are shown in SM Table .

**SM Table 5.** Characterization of the municipal solid waste generated in the Great Vitória Metropolitan Region

	Recyclables			Biowaste	Undifferentiated	
	Paper	Metal	Glass	Organic	Commingled	
Magazines	0.20%					
Newsprints	0.80%					
Juice cartons (Multilayered packaging)	1.10%					
Office paper	9.95%					
Other clean cardboard	10.21%					
Beverage cans (Aluminum)		0.11%				
Food cans (Ferrous metal)		1.02%				
Brown glass (Colored glass)			1.52%			
Clear glass			7.58%			
Plastic bottles (PET)				0.37%		
Plastic products (Other plastic)				0.75%		
Hard plastic				2.06%		
Non-recyclable plastic (Styrofoam)				2.97%		
Soft plastic (2D Plastic)				4.01%		
Pruning waste				0.33%		
Dirty paper				0.80%		
Animal food waste				5.88%		
Vegetable food waste				43.14%		
Other combustibles (Foam)					0.09%	
Shoes, leather					0.19%	
Rubber					0.23%	
Sanitary waste					1.28%	
Textiles					2.11%	
Other non-combustibles					3.18%	
Hazardous waste (Batteries)					0.11%	
<b>SUM</b>	<b>22.26%</b>	<b>1.13%</b>	<b>9.10%</b>	<b>10.16%</b>	<b>50.15%</b>	<b>7.08%</b>

Source: Adapted from Ramalho et al. (2021).

**SM Table 6.** Landfill diversion targets for recyclable waste, proposed by the Brazilian Solid Waste Plan for Southeast Brazil (PLANARES)

Year:		2015	2019	2023	2027	2031	2040
Proposed Recyclable waste diversions	Pessimistic*	30	37	42	45	50	-
	Moderate*	40	55	65	70	70	-
	Optimistic*	70	70	70	70	70	-
	PLANARES 2020**	-	-	-	-	-	25.8
Proposed Biowaste diversions	Pessimistic*	25	35	45	50	55	-
	Moderate*	35	45	55	65	70	-
	Optimistic*	70	70	70	70	70	-
	PLANARES 2020**	-	-	-	-	-	18.1

Note: \*Diversion targets proposed by MMA (2012). \*\*Latest diversion target from MMA (2020).

### Currency data

SM Table contains the mean monthly and yearly quote for the US Dollar (USD) in Brazilian Reais (BRL), which was used to convert the values in BRL to USD, taking into account the year of the data. The average value between December 2017 and November 2022 was \$1=R\$4.60 or R\$1= \$0.2176.

**SM Table 7.** Brazilian real value in US dollars.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sep.	Oct.	Nov.	Dec.	Avg.
2022	5.7127	5.5349	5.1881	5.1314	4.7158	5.1075	5.1119	5.4014	5.0925	5.2211	5.2824		5.23
2021	5.0968	5.2714	5.3815	5.6296	5.6234	5.2701	5.0874	5.1000	5.2474	5.2576	5.4510	5.4199	5.32
2020	4.0949	4.1622	4.3163	4.7362	5.2579	5.8229	5.1883	5.3491	5.3852	5.2728	5.6172	5.4854	5.06
2019	3.9090	3.7049	3.7155	3.8344	3.8730	4.0031	3.8813	3.7463	4.0188	4.0616	4.1488	4.1831	3.92
2018	3.3182	3.1963	3.2208	3.2859	3.4105	3.6753	3.7738	3.8745	3.9134	4.1879	3.7332	3.7924	3.62
2017												3.2834	3.19

Source: BCB – Brazilian Central Bank (2022a).

To update the monetary values to the current year, the values shown in SM Table were used to represent the annual inflation in Brazil.

**SM Table 8.** Brazilian Wide Consumer Price Index (IPCA).

IPCA	%
Dec.2017	2.95
Dec.2018	3.75
Dec.2019	4.31
Dec.2020	4.52
Dec.2021	10.06

Source: BCB (2022b).

### Waste Logistics

The transport distances used to calculate the transport expenses, which are a distance function, are presented in SM Table (Ramalho *et al.*, 2021). The distance between town centers and transfer stations was not used but was included in the table to show that they do not exceed the maximum economy distance of 25 km (Chen and Lo, 2016). And Viana is the only municipality that sends its waste directly to Cariacica, slightly exceeding 25 km.

**SM Table 9.** Distances between Great Vitória Metropolitan Region facilities in kilometers

Collection	Transport
------------	-----------

Municipality	Town center	Transfer Station
	→ TS distance	→ Landfill
Cariacica	0	13.7
Guarapari	11	39.3
Serra	19.7	30.6
Viana	0	28.9*
Vila Velha	6.3	18.9
Vitória	5	25.2

Note: \*Viana sends its waste directly to the landfill and does not have a transfer station. Source: Adapted from Ramalho et al. (2021).

### CAPEX, OPEX and revenues

The total costs and revenues of the facilities and scenarios are shown in Table . Starting with the facilities, waste collection is one of the most expensive parts of the system, next to final disposal. Like in other studies, the logistics costs represented about half of the total costs (Colvero *et al.*, 2020; Ferronato *et al.*, 2019; Lohri *et al.*, 2014; Teixeira *et al.*, 2014). These costs reflect salaries, vehicle maintenance, collection routes and facility location (Hannan *et al.*, 2020), which are complex issues that must be carefully analyzed and optimized with specific tools (Sulemana *et al.*, 2018).

Logistics was primarily affected by the amount of source-separated collection, which roughly doubled the unit cost of commingled collection, as seen in Table 3 of the Manuscript (Reichert, 2013). Despite that, Tang *et al.* (2018) show that commingled collection with later sorting costs even more while being more damaging to the environment than source-separated collection. But increasing source-separated collection demands citizens to collaborate in this action, which is not easy and demands efficient strategies. Different authors proposed measures like digitization (Kurniawan *et al.*, 2021); door-to-door collection (Gallardo *et al.*, 2021), which is the established system in GVMR; MSW sorting guidance and coherence between the home-sorting action and waste destination (Xiao *et al.*, 2020); making the waste producers physically and financially responsible for the waste collection and recycling, as well as incentivizing them economically (Takahashi, 2020). In short, to be attractive, waste collection should be transparent, convenient, user-friendly and economically beneficial for the public.

**Table 10.** Total capital and operational expenses (CAPEX and OPEX), revenues of the facilities and scenarios proposed for Great Vitória Metropolitan Region (in US\$ and extrapolated to the year 2022)

(US\$)	CAPEX		OPEX		REVENUE	
Facilities	HIGH	LOW	HIGH	LOW	HIGH	LOW
Collection	-	-	781.75	427.60	-	-
Collection	-	-	781.75	427.60		
Transport	-	-	24.26	33.09	-	-
Transfer Station	0.48	0.87	60.41	82.39	-	-
Materials Recovery Facility	1.09	0.40	286.56	105.62	378.95	139.67
Open Composting	118.90	34.26	157.29	49.37	137.41	24.43
Closed Composting	178.47	49.70	133.50	40.85		
Anaerobic digestion	347.67	232.75	381.98	119.91	352.08	73.44
Incineration	206.90	579.46	187.81	462.48	239.71	777.64
Landfill	-	-	182.90	662.68	53.44	

(US\$)	Total CAPEX		Total OPEX		Total REVENUE	
Scenarios	HIGH	LOW	HIGH	LOW	HIGH	LOW
OC+LDF	120.46	35.53	1,493.17	1,360.75	569.80	217.54
CC+LDF	180.04	50.97	1,469.38	1,352.23		
AD+LDF	349.23	234.02	1,717.86	1,431.28	784.48	266.55
OC+WtE	327.36	614.99	1,498.08	1,160.55	956.07	941.74
CC+WtE	386.93	630.43	1,474.30	1,153.03		
AD+WtE	556.13	813.49	1,722.78	1,231.08	970.74	990.75

Legend: OC – Open Composting, CC – Closed Composting, AD – Anaerobic Digestion, LDF – Landfill, WtE – Incineration, NPV – Net Present Value.

Although collection is the most expensive part of the system (45-53% of total costs) in the high diversions scenarios, it is slightly less expensive than the landfill in low diversions scenarios with landfills, representing 30-32% of the total costs, because most of the waste is simply commingled and sent to landfills. One way to reduce the collection expenses would be to use bring collection, in which residents dispose of their waste in collection bins instead of door-to-door collection (Pires *et al.*, 2017). But this action could compromise the achievement of the diversion targets, as the scientific literature suggests (Abbott *et al.*, 2011; Di Maria and Micale, 2013; Lakhan, 2014). There are other ways to tackle this issue, such as replacing diesel by biomethane produced in AD (Pérez *et al.*, 2017), and hybrid collection systems (Costa *et al.*, 2019; Gallardo *et al.*, 2012; Martinho *et al.*, 2017), which are a mix of Bring and door-to-door collection. In any case, because of the very different fuel consumption and particularities of each area (Gredmaier *et al.*, 2013), a

thorough, careful analysis must be carried out before taking any decisions regarding the waste collection service. Still, on logistics, it is worth mentioning that the transport component is much less expensive than the collection component, 7% and 36% in high and low diversions scenarios, respectively. Additionally, the transport component is actually less expensive the more waste is diverted from landfills, which is the opposite of collection. This is because the distances between TSs and MRFs are, correctly, smaller than the distance between TSs and landfills (SM Table 9), as in Ramalho *et al.* (2021).

Landfills, where almost all MSW in GVMR currently ends up, are another costly part of the system in terms of OPEX. This is because they are heavily engineered, with techniques like biogas capture, bottom liners to prevent soil contamination, leachate collection and treatment to improve their environmental performance (Madon *et al.*, 2019). Mehta *et al.* (2018) have divided landfill costs into five different categories: waste transport, land acquisition, construction and operation, leachate management and landfill gas flaring system. Although, the construction costs were separated from the steep operating costs. In fact, the landfill had the highest OPEX of all facilities in the low diversions flows, 3.6 times higher than in high diversions. As for the revenues, since the electricity generation from landfill gas is at an experimental stage in Cariacica and was recently expanded (Marca Ambiental, 2021, 2020), the potential capacity is not fully utilized yet.

Regarding the different biowaste treatments, AD is much more cost-intensive than composting in terms of investment and operation. Yet it generates more revenues, as in Lin *et al.* (2019). As shown in Table , the CAPEX difference between these two types of biowaste treatment is much higher in LOW diversions (almost 5 -7 times higher) than in HIGH diversions (roughly double or triple). As for the OPEX, the difference between AD and composting is almost the same, independently of the diversion targets (about 2.4-2.9 times more, depending on the type of composting and target). As for the revenues, the difference AD and composting in high and low diversions scenarios is 1.4 and 1.9 times higher in AD, respectively. Thus, the amount of waste received by AD is significant when choosing this technology, because the increase in CAPEX is much more substantial in smaller facilities that treat smaller amounts of biowaste (Colvero *et al.*, 2020; Tsilemou and Panagiotakopoulos, 2006). Therefore, AD is preferable for centralized facilities that deal with large waste quantities, while composting would be more favorable for decentralized solutions (Colvero *et al.*, 2020; Lin *et al.*, 2019). Between Open and Closed Composting, this last option should be preferred even though the CAPEX is higher, as not only the OPEX is lower, but so are the environmental impacts (Boldrin *et al.*, 2011; Lima *et al.*, 2018).

Regarding the scenarios (second part of Table ), which combine different biowaste and disposal facilities, the ones with incineration (OC+WtE, CC+WtE, AD+WtE) generated more revenue than their counterparts with landfills (OC+LDF, CC+LDF, AD+LDF) because of the electricity sales

(Abdallah *et al.*, 2021), even though the OPEX is similar. In fact, the AD+WtE scenario with LOW diversions generated even more revenue than the scenario than its HIGH diversions counterpart, due to the increased waste incineration and consequent energy recovery. On the other hand, the scenarios with incineration have a higher CAPEX, because the investment in new landfills is null, as they already exist. This will have repercussions on the fees to be charged to the citizens, which will be further discussed in the next section. To compare the investment in new incineration facilities with new landfills, an analysis with primary CAPEX data, that was unavailable, would be necessary.

A point worth noting is that the LOW diversions scenarios with incineration are considerably more expensive than their HIGH diversions counterparts, again because of the high CAPEX of incineration (Aleluia and Ferrão, 2017). Therefore, even if AD is an expensive technology, the scenario AD+WtE with HIGH diversions is less costly overall than the other two environmentally unfavorable scenarios that associate an inferior treatment for biowaste (OC+WtE and CC+WtE) with LOW diversions, while also generating slightly more revenue. This is explained by the sales of electricity generated from biogas and the high-valued digestate that can be used on land (Rajendran and Murthy, 2019).

The scenarios with AD have a much higher CAPEX than those with composting, but the revenues are not much higher. So, the much better environmental performance of this treatment is obtained at a higher cost. However, the study by Murphy and Power (2006) suggested that using upgraded biogas as a vehicular fuel, not analyzed in this study, would significantly improve the economic performance of AD. It is worth noting that the OPEX of the scenarios with OC (which is currently used in Cariacica) are slightly higher than those with AD. Therefore, the scenarios with OC would probably be the last option because of increased methane emissions (Al-Rumaihi *et al.*, 2020), not to mention emissions of odorous and hazardous compounds like acetaldehyde (Duan *et al.*, 2022), while still not being cheap to run.

### Service fees

The calculated MSW management service fees that have to be charged to the population to attain the different internal rates of return (0%, 8% and 16%) for the municipalities of GVMR are shown in a weight basis, and SM Table , in a yearly basis.

**SM Table 11.** Municipal solid waste management service fees per metric ton charged to the population in Great Vitória Metropolitan Region (US\$·t<sup>-1</sup>).

HIGH DIVERSIONS SCENARIOS							LOW DIVERSIONS SCENARIOS					
0% Internal Rate of Return												
US\$	Cariacica	Guarapari	Serra	Viana	Vila Velha	Vitória	Cariacica	Guarapari	Serra	Viana	Vila Velha	Vitória
OC+LDF	70.90	84.63	71.62	80.00	71.48	71.08	83.67	99.88	84.52	94.42	84.35	83.89
CC+LDF	75.16	89.72	75.93	84.81	75.77	75.36	84.75	101.17	85.62	95.64	85.45	84.98
AD+LDF	77.92	93.02	78.72	87.93	78.56	78.13	96.49	115.18	97.48	108.88	97.28	96.74
OC+WtE	74.76	89.25	75.53	84.37	75.38	74.96	78.91	94.20	79.72	89.05	79.56	79.12
CC+WtE	79.07	94.39	79.88	89.23	79.72	79.28	80.14	95.67	80.96	90.44	80.80	80.36
AD+WtE	81.27	97.01	82.10	91.71	81.94	81.48	93.92	112.12	94.89	105.99	94.70	94.17
8% Internal Rate of Return												
OC+LDF	81.21	96.95	82.04	91.65	81.88	81.43	87.48	104.42	88.37	98.72	88.20	87.71
CC+LDF	90.73	108.31	91.66	102.39	91.48	90.97	89.87	107.28	90.79	101.42	90.61	90.11
AD+LDF	103.65	123.74	104.72	116.97	104.51	103.93	115.86	138.31	117.05	130.75	116.81	116.17
OC+WtE	102.44	122.28	103.49	115.60	103.28	102.71	138.27	165.06	139.69	156.03	139.40	138.64
CC+WtE	112.26	134.01	113.41	126.68	113.18	112.56	141.37	168.76	142.82	159.54	142.53	141.75
AD+WtE	122.04	145.68	123.29	137.72	123.04	122.36	168.32	200.93	170.05	189.95	169.70	168.77
16% Internal Rate of Return												
OC+LDF	94.69	113.04	95.66	106.86	95.47	94.94	92.11	109.95	93.05	103.94	92.87	92.35
CC+LDF	111.14	132.67	112.28	125.42	112.05	111.43	96.24	114.89	97.23	108.61	97.03	96.50
AD+LDF	137.33	163.94	138.74	154.98	138.46	137.70	141.15	168.50	142.60	159.29	142.31	141.52
OC+WtE	138.69	165.56	140.11	156.51	139.83	139.06	216.65	258.62	218.87	244.48	218.43	217.22
CC+WtE	155.78	185.97	157.38	175.80	157.06	156.20	222.25	265.31	224.53	250.81	224.08	222.84
AD+WtE	175.39	209.38	177.19	197.93	176.84	175.86	266.50	318.13	269.23	300.74	268.69	267.21

Note: OC – Open composting, CC – Closed composting, AD – Anaerobic digestion, LDF – Landfill, WtE – Incineration.

**SM Table 12.** Municipal solid waste management yearly service fees per inhabitant in Great Vitória Metropolitan Region (US\$·inhabitant<sup>-1</sup>·year<sup>-1</sup>).

HIGH DIVERSIONS SCENARIOS							LOW DIVERSIONS SCENARIOS					
0% Internal Rate of Return												
US\$	Cariacica	Guarapari	Serra	Viana	Vila Velha	Vitória	Cariacica	Guarapari	Serra	Viana	Vila Velha	Vitória
OC+LDF	20.12	34.01	18.31	18.44	26.46	32.04	23.74	40.13	21.61	21.76	31.23	37.81
CC+LDF	21.22	36.05	19.42	19.55	28.05	33.97	23.93	40.65	21.89	22.04	31.63	38.30
AD+LDF	23.09	37.38	20.13	20.27	29.08	35.22	28.59	46.28	24.93	25.10	36.01	43.61
OC+WtE	18.00	35.86	19.31	19.44	27.90	33.79	19.00	37.85	20.39	20.52	29.45	35.66
CC+WtE	18.92	37.93	20.43	20.57	29.51	35.73	19.18	38.44	20.70	20.84	29.91	36.22
AD+WtE	20.58	38.98	20.99	21.14	30.33	36.73	23.79	45.05	24.26	24.43	35.06	42.45
8% Internal Rate of Return												
OC+LDF	23.04	38.95	20.98	21.12	30.31	36.70	20.12	34.01	18.31	18.44	26.46	32.04
CC+LDF	25.62	43.52	23.44	23.60	33.86	41.01	21.22	36.05	19.42	19.55	28.05	33.97
AD+LDF	30.71	49.72	26.78	26.96	38.69	46.85	23.09	37.38	20.13	20.27	29.08	35.22
OC+WtE	24.66	49.13	26.46	26.64	38.23	46.30	18.00	35.86	19.31	19.44	27.90	33.79
CC+WtE	26.87	53.85	29.00	29.20	41.90	50.74	18.92	37.93	20.43	20.57	29.51	35.73
AD+WtE	30.91	58.54	31.53	31.74	45.55	55.15	20.58	38.98	20.99	21.14	30.33	36.73
16% Internal Rate of Return												
OC+LDF	26.87	45.42	24.46	24.63	35.34	42.80	26.13	44.18	23.79	23.96	34.38	41.63
CC+LDF	31.38	53.31	28.71	28.91	41.48	50.23	27.17	46.16	24.86	25.03	35.92	43.49
AD+LDF	40.69	65.87	35.48	35.72	51.26	62.07	41.82	67.70	36.46	36.71	52.68	63.79
OC+WtE	33.39	66.52	35.83	36.07	51.76	62.68	52.15	103.92	55.97	56.35	80.86	97.91
CC+WtE	37.28	74.72	40.24	40.52	58.14	70.41	53.19	106.60	57.42	57.81	82.95	100.45
AD+WtE	44.42	84.13	45.31	45.62	65.46	79.27	67.50	127.83	68.85	69.31	99.47	120.44

Note: OC – Open composting, CC – Closed composting, AD – Anaerobic digestion, LDF – Landfill, WtE – Incineration.

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