https://doi.org/10.1590/S1413-415220230002

Scientific Article

Cost-benefit analysis of technological changes: case of a management solid waste consortia in the metropolitan region of Curitiba, Brazil

Análise custo-benefício para mudança de tecnologia: o caso de um consórcio de gerenciamento de resíduos sólidos na região metropolitana de Curitiba, Brasil

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ABSTRACT

Huge increases in the volume of waste produced by society have created an urgent need for new and improved municipal solid waste (MSW) processes. In many countries, traditional methods to manage MSW, such as landfills, have been abandoned in favor of more effective and environmentally efficient technologies. These include gasification (decomposition at high temperatures), recycling, and composting (of organic matter). The purpose of this research was to assess certain financial, social, and environmental indicators, especially the IRR and cost-benefit ratio of changing the technologies used in MSW processing. The research focuses on assessing these changes in the CONRESOL area — a consortium that covers almost all the municipalities in the metropolitan region of Curitiba, Brazil. To this end, scenarios were proposed that apply various technological combinations and two collection fees. Of the three proposed scenarios, the one with the best socioeconomic and environmental results (Internal Rate of Return, Net Present Value, Discounted Payback, and Benefit/Cost ratio) combines gasification, recycling, and composting. This scenario generated the least GHG emissions and the highest number of jobs.

Keywords: municipal solid waste; gasification; recycling; composting; cost-benefit analysis; technologies.

RESUMO

O enorme aumento no volume de resíduos produzidos pela sociedade criou uma necessidade urgente de processos novos e melhores para tratamento dos resíduos sólidos urbanos (RSU). Em muitos países, os métodos tradicionais de gerenciamento de RSU, como aterros sanitários, foram abandonados em favor de tecnologias mais eficazes e ambientalmente eficientes. Eles incluem gaseificação (decomposição em altas temperaturas), reciclagem e compostagem (de matéria orgânica). O objetivo desta pesquisa foi avaliar alguns indicadores financeiros, sociais e ambientais, especialmente a taxa interna de retorno, a emissão de gases de efeito estufa, a geração de empregos e a relação custo-benefício da mudança de tecnologia utilizada no processamento dos RSU. A pesquisa se concentra em avaliar essas mudanças na área do Consórcio Intermunicipal para Gestão dos Resíduos Sólidos Urbanos (CONRESOL) — um consórcio que abrange quase todos os municípios da região metropolitana de Curitiba, Brasil). Para tanto, foram propostos cenários que aplicam diversas combinações tecnológicas e duas taxas de cobrança. Dos três cenários propostos, aquele com os melhores resultados socioeconômicos e ambientais (Taxa Interna de Retorno, Valor Presente Líquido, *Payback* Descontado e Relação Benefício/Custo) combina gaseificação, reciclagem e compostagem. Esse cenário gera as menores emissões de gases de efeito estufa (GEE) e o maior número de empregos.

Palavras-chave: resíduos sólidos urbanos; gaseificação; reciclagem. compostagem; análise custo-benefício; tecnologias.

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Conflicts of interest: the authors declare no conflicts of interest.
Funding: none.
Received on: 01/06/2023 – **Accepted on:** 06/07/2023

INTRODUCTION

In developed countries, landfills have fallen into disuse, while in poor and developing countries this municipal solid waste (MSW) process persists on a large scale. In most developed countries, strategies to reduce the volume of MSW include environmental education for families and company managers. The aim is to reduce the amount of MSW and to process the waste using efficient technologies that minimize environmental impacts (TILBURY, 2004; KOPNINA, 2014; MALINAUSKAITE *et al.*, 2017).

Consumers are required to segregate metal, glass, and paper, which are then forwarded to recycling companies (GORDON; BERTRAM; GRAEDEL, 2006). The remaining MSW volume contains organic and other non-recyclable materials. The organic material is then taken for composting and used as a natural fertilizer. Non-organic and non-recyclable materials undergo some kind of thermal processing (such as incineration) (MURRAY, 1999; MEDINA, 2010; GARDNER, 2016).

The incineration process emits varying amounts of greenhouse gases (GHG). Certain recent thermal technologies, such as gasification, aim to perform the same function as traditional incineration plants, while reducing the volume of GHG emissions (DONG *et al.*, 2018; SUN *et al.*, 2021). Processes such as gasification, composting, and recycling are, therefore, examples of MSW treatment processes considered environmentally friendly.

However, in some societies, this combination is not economically viable, as the necessary financial investment requires an increased household collection fee. In other words, for many low/middle-income societies, increasing such charges constitutes a barrier to these environmentally friendly processes (ALAM; AHMADE, 2013; BUNDHOO, 2018).

In addition to the collection fee, other sources of investment are required. In this context, processing MSW in gasification plants enables the production of electricity which, if sold, constitutes financial inflow. In order to reduce an MSW company's operational expenditure, it can use some of this electricity to supply its own needs. Thus, from a large volume of MSW, a gasification plant can produce large amounts of energy (SRIWANNAWIT; ANISA; RONY, 2016; HADIDI; OMER, 2017; RAHMAN; AZEEM; AHAMMED, 2017; ABDALLAH *et al.*, 2018; MABALANE *et al.*, 2021).

Composting and recyclable segregation plants also provide financial inflows, since recyclable materials and compost (black organic matter) can be sold in regional markets. All these financial inputs minimize costs for society. In addition to finance, these processes increase the ecological content of MSW treatment and provide environmental benefits for society (SONG; WANG; LI, 2013; ARAFAT; JIJAKLI; AHSAN, 2015; SMITH *et al.*, 2015).

With gasification, recycling, and composting, it is possible to attain greater use, reuse, and recycling of materials, in other words, to apply the 3R principle (reduce, reuse, and recycle) (DAMANHURI *et al.*, 2009; CHOWDHURY *et al.*, 2014).

There are many published studies on economic analyses of MSW and that used methodologies that also include social and environmental issues, for example: Life Cycle Assessment, Circular Economy, Cost-Effectiveness Analysis, etc. However, it would be the task of a bibliometric analysis on the subject to present all these references.

Instead, this article is dedicated to an analysis of the socioeconomic and environmental feasibility of projects, such as technological alternatives for landfill replacement. That is, it is not an analysis of the operational efficiency of technologies, but the effects of combining technologies in the treatment of MSW on socioeconomic and environmental issues. Therefore, it is necessary to use a methodology that estimate the return of these projects to society. This return must consider financial, environmental, and social issues. Therefore, the methodology that presents this analytical complexity is the cost-benefit analysis (CBA), whose results are indicators capable of guiding the choice of the best project. These indicators are the benefit/cost ratio, the internal rate of return, and others.

No CBA research were found in the literature that evaluated the change from landfill to the MSW processing systems proposed in this study: gasification; recycling; and composting. These technologies are well described in Christensen (2011), Ludwig, Hellweg and Stucki (2012) and Agbejule *et al.* (2021), however, these studies do not analyze the CBA of these processing strategies within a complex system that combines multiple technologies.

Butt *et al.* (1998) studied the economic assessment of recycling sewage by anaerobic co-digestion with incineration and composting of MSW by CBA. This study is similar to the present article. However, incineration and composting technologies are different from those analyzed here.

Sharma and Chandel (2021) carried out a Life Cycle Cost analysis and projected scenarios with certain MSW treatment technologies. However, this research did not quantify the benefit/cost ratio, the balance of changes in GHGs (that is, the environmental benefits) or the difference in the number of jobs. An extensive review of Life Cycle Assessment (LCA) studies can be found in Astrup *et al.* (2015).

The most frequently published surveys provide separate economic assessments of certain MSW treatment technologies. For example, whether recycling, composting, or an energy recovery process is economically viable. In some cases, studies examine a reduction in GHG emissions alongside a set of financial indicators (MCCREA *et al.*, 2009; CHANG *et al.* 2012; NG *et al.*, 2014; CHEN, 2016; ELSAID; AGHEZZAF, 2016; HARAGUCHI; SIDDIQI; NARAYANAMURTI, 2019; LIU *et al.*, 2020). These do not, therefore, consider a sequence of combined technologies that balances GHG emissions, jobs, and financial matters.

Many studies assessed energy-related GHG emissions (PARSHALL *et al.*, 2011); the MSW sector needs to view other issues, especially at the global context, related to jobs and financial return. Waste-to-energy (WTE) technologies have some clear advantages in favor of their adoption, *e.g.* minimizing the amount of waste sent to landfills (GOHLKE; MARTIN, 2007; LOMBARDI; CARNEVALE; CORTI, 2015), and generating heat and electricity (AYODELE; OGUNJUYIGBE; ALAO, 2017). Recently, energy recovery (rate) has been increasing and the volume of GHG emissions, reducing (CASTALDI; THEMELIS, 2010).

Given these possibilities, this study focused on the economic assessment of the transition from landfill to more ecologically friendly technologies for the treatment of MSW in one part of the metropolitan region of Curitiba in the state of Paraná, Brazil. The municipal governments of these 23 municipalities (Figure 1) charge companies and families with MSW collection fees and pool these financial resources in the Intercity Consortia for Urban Solid Waste Management (*Consórcio Intermuncipal para Gestão dos Resíduos Sólidos Urbanos* – CONRESOL). Depending on the volume of MSW to be treated, CONRESOL uses this money to pay a waste treatment company.

This geographical area of the consortium is formed by a large part of the municipalities of the metropolitan region of Curitiba, capital of the state of

Paraná (Brazil). Therefore, it is an urban agglomeration with the largest population of the state (about 3.5 million) and has a reasonable human development compared to other regions of the state and of Brazil. But, when analyzing the municipalities individually, one sees that about half of them have a Human Development Index (HDI) below 0.7, *i.e.*, low. The largest municipality in terms of population is Curitiba (almost 2 million inhabitants), in addition to producing the largest amount of MSW (458 thousand tons per year). The total MSW generated in the municipalities of the consortium is more than 832 thousand tons per year. This can be seen in Table 1.

This research aimed to measure socioeconomic and environmental indicators of MSW treatment technologies (from landfill to a system that combines gasification, recyclable segregation, and composting plants). Two charges (the actual collection fee and willingness-to-pay) and certain scenarios containing combinations of these technologies are depicted here.

The research is divided into 5 sections. After the introduction, the first section outlines the methodology, the second section presents the results and discussions, an another section presents the results and discussions, finally the last section presents our main conclusions.

METODOLOGY

Scope of the research

CBA methodology is widely used to address socioeconomic and environmental issues. In order to perform this assessment, the following objectives needed to be fulfilled:

- Estimating the population growth and volume of MSW over the investment amortization period (30 years – landfill lifetime according to Brazilian environmental law);
- Quantifying gasification, composting and recycling equipment, in line with the amount of MSW to be processed;
- Calculating the costs, inflows, jobs, GHG emissions, and financial indicators (net present value – NPV, internal rate of return – IRR, Discounted Payback, etc.) in reference to landfill and scenarios;
- Conducting a cost-benefit analysis;
- Performing a sensitivity analysis using Monte Carlo simulations.

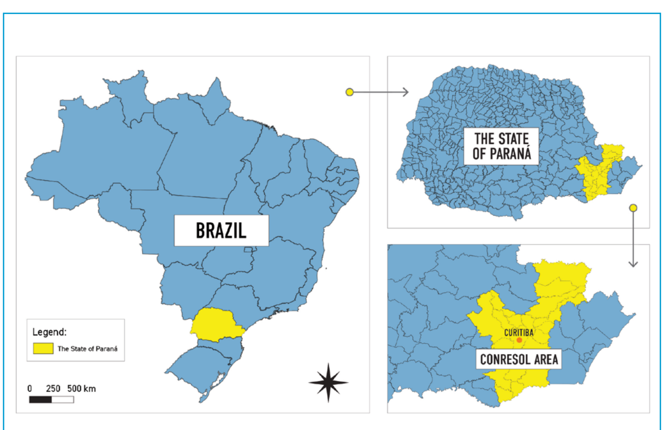

Figure 1 – CONRESOL (consortium of 23 municipalities) area in the state of Paraná, Brazil.

Technologies and scenarios

Three technology scenarios were proposed for the cost-benefit analysis, according to the material flows.

Thus, in summary, our scenarios are:

- Scenario 1: Gasification;
- Scenario 2: Gasification and Recycling;
- Scenario 3: Gasification, Recycling, and Composting.

Segregation of recyclables

Despite the selective collection of recyclables prior to landfill, a certain volume remains in raw MSW (uncontaminated metals, plastics, glass, and paper). Thus, the recyclable segregation process can be anticipated. Segregation equipment include: mats, sieves, compressors, computers, artificial intelligence software, etc. In this technology, segregation occurs through gravity and at speed using (2D and 3D) optical identification software (MELO, 2015).

Composting

An oxidative, biological, and aerobic biodegradation process that converts organic matter into compost, which can be used as organic fertilizer (BIDONE; POVINELLI, 1999). We proposed the use of "Dano" equipment for sorting,

Table 1 – Socioeconomic and MSW data of municipalities in the CONRESOL consortium.

Municipality	MSW Volume (tons/year - 2020)[1]	Population (Inhabitants - 2020)[2]	Human Development Index (HDI - 2010)[3]
Curitiba	458,666	1,933,105	0.823
São José dos Pinhais	76,719	323,340	0.758
Colombo	57,829	243,726	0.733
Araucária	34,129	143,843	0.740
Pinhais	31,357	132,157	0.751
Campo Largo	31,320	132,002	0.745
Almirante Tamandaré	28,146	118,623	0.699
Piraquara	26,820	113,036	0.700
Fazenda Rio Grande	23,776	100,209	0.720
Campina Grande do Sul	10,271	43,288	0.718
Campo Magro	6,956	29,318	0.701
Itaperuçu	6,794	28,634	0.637
Mandirituba	6,375	26,869	0.655
Quatro Barras	5,590	23,559	0.742
Quitandinha	4,520	19,049	0.680
Contenda	4,409	18,584	0.681
Tijucas do Sul	4,002	16,868	0.636
Bocaiúva do Sul	3,071	12,944	0.640
Balsa Nova	3,070	12,941	0.696
Piên	3,024	12,746	0.694
Agudos do Sul	2,223	9,371	0.660
Tunas do Paraná	2,081	8,769	0.611
Adrianópolis	1,404	5,919	0.667
Total	832,553	3,508,900	

Source: [1]CONRESOL (2018); [2]IPARDES (2018); [3]PNUD (2010).

milling raw organic matter, and horizontal composting (REIS, 2005). "Dano" is assembled by rotating cylinders of approximately 3 meters in diameter and 35 meters in length. These cylinders have a production range of 50 tons of organic matter and a retention time of 3 days. The residue is stirred in the cylinders at a speed of approximately 1 rpm. The product obtained is called pre-compost and the composting process is completed in windrows, turned biweekly for 50 days. The material must then be sieved (SILVA *et al.*, 2005).

Gasification by anaerobic pyrolysis

A thermochemical degradation reaction at temperatures ranging from 800 to 900°C. This process recovers approximately 80% of the energy from the burned materials and turns them into oil, coal, and gases, according to the technical efficiency of the equipment planned for this study (IPK-PIROFLEX, 2019). Gasification produces electrical energy (WTE process). This technology was chosen because it is currently often used in Brazil, maybe as a tendency. In other words, it is a known technology in world terms with expansion of use cases and there are some plants in Brazil, for example in the municipality of Boa Esperança, state of Minas Gerais (MENEZES NETO *et al.*, 2021); in the municipality of Mafra, state of Santa Catarina (ARRUDA, 2020); and other plants under implementation and operation (TULIO, 2020).

Framework structure

For an overview of the methodology, the steps of the research are described in Figure 2. It shows the sequence of calculations, from the partial results to the final results, that is, the use of parameters and inputs, with the references of each mathematical formula. Calculation formulas, as well as their explanation, can be found in the following sections.

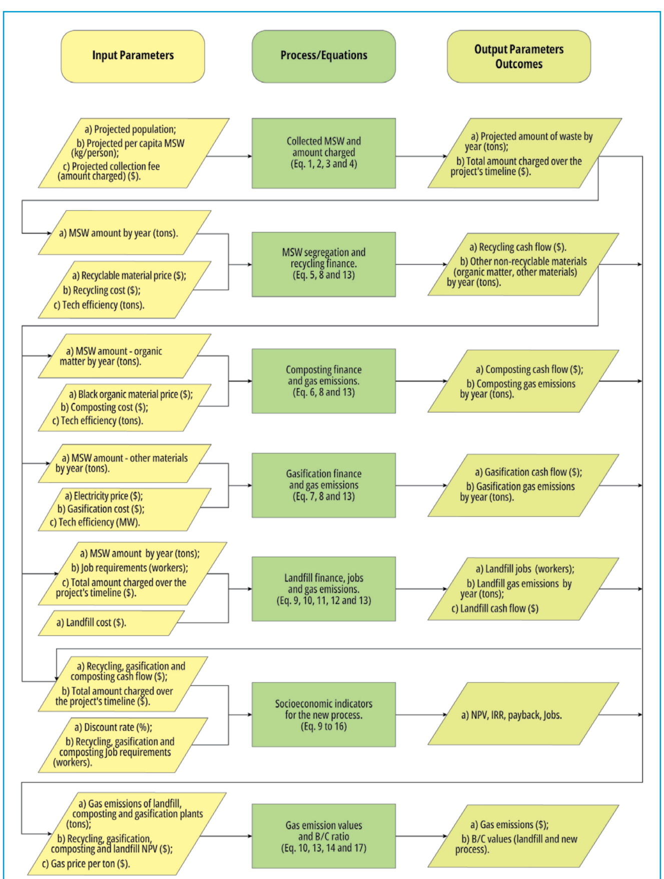

Figure 2 – Methodology steps.

Collection fee projections, population, and MSW feedstock

Municipal governments pay the company to process the MSW via CONRESOL. The amount paid to this company is thus calculated by Equation 1:

$$C_t = W_t . S_t . d^t \quad (1)$$

Where:

C_t: Total value paid to the MSW processing company (year "t");
W_t: Total volume of MSW to be processed (year "t");
S_t: Collection fee for processing the MSW in US$ per ton – (year "t");
d: Discount rate;
t: Project lifetime.

To estimate population growth during the project, the following exponential function was used, according to Leite, Silva and Souza (2011) (Equation 2):

$$P_t = P_0 . e^{rt} \quad (2)$$

Where:

P_t: Population at time "t" ("t" ranging from 0 to n);
P_0: Actual population;
r: Population growth rate.

To estimate the MSW production parameter (proportion of MSW production, as a function of the population) (Equation 3):

$$\alpha_z = W_z / P_0 \quad (3)$$

Where:

a_Z: MSW production parameter (proportion of "Z" (kind of) MSW produced by P_0 population);
W_Z: Total volume of "Z" MSW produced by the P_0 population.

Raw MSW was used to estimate this parameter. In order to estimate the volume of MSW for each type of waste (recyclables, organic matter for composting, and other MSW for gasification) for the duration of each project, the following linear function was calculated (Equation 4):

$$R_{z,t} = P_t . \alpha_z \quad (4)$$

Where:

$R_{Z,t}$: Quantity of "Z" waste to be processed, time "t" ("t" ranging from 0 to n).

MSW segregation and recycling

Segregating MSW produces a certain amount of recyclable materials, organic matter, and other MSW. The volume of this material is given by Equation 5:

$$X_{z,t} = R_{z,t}.\theta_z \quad (5)$$

Where:

$X_{Z,t}$: Volume of "Z" MSW (recyclables, organic matter, and other MSW) (tons), time "t";

$R_{Z,t}$: Raw MSW produced by households and companies for processing, time "t" (with "t" ranging from 0 to n);

θ_Z: the MSW segregation parameter of "Z" waste (between 0 and 1).

This is the amount of recyclables, organic matter, and other MSW as a proportion (per ton) of the total volume of MSW.

Composting

Processing the organic matter produces a certain amount of black organic matter. The annual quantities of this product are obtained by Equation 6:

$$BM_t = X_{z,t}.\beta \quad (6)$$

Where:

BM_t: Quantity of black organic matter (tons), time "t";

β: Conversion parameter of organic matter into black organic matter (ranging between 0 and 1) – percentage of amount of compost produced from processing the volume (per ton) of organic matter.

Electricity production

Gasification recovers energy from MSW and produces electrical energy. Some of the electrical energy produced is used to operate all the MSW processing facilities. The net amount of electricity is therefore given by Equation 7:

$$EL_t = \varepsilon_Z \,.\, X_{z,t} - U_t \quad (7)$$

Where:

EL_t: Average electrical power produced (MW/1,250 tons/month), time "t";

ε_Z: Energy production coefficient of "Z" MSW (MW/ton);

U_t: Quantity of electrical energy used by the MSW company's facilities.

Black organic matter, recyclables, and electricity monetary values

The monetary inflows from the sale of electricity, recyclables and organic compost are calculated by Equation 8:

$$V_{e,t} = \sum_{t=1}^{n} S_{e,t}.P_{e,t} \quad (8)$$

Where:

$V_{e,t}$: Value of the "e" product sold, time "t";

$S_{e,t}$: Quantity of the "e" product sold, time "t";

$P_{e,t}$: Price of the "e" product (US$), time t;

e: Product sold;

$X_{Z,t}$: Quantity of recyclables (tons) by type;

BM_t: Quantity of black organic matter (tons);

EL_t: Quantity of electricity (MW).

Quantities and values of greenhouse gas emissions

Landfill, composting, and gasification of GHG emissions are calculated by Equation 9:

$$GH_{c,y,t} = X_{z,t}\,.\gamma_{c,y} \quad (9)$$

Where:

$GH_{c,y,t}$: Quantity of the "c" GHG emitted (tons);

$Y_{c,y}$: emission coefficient of the "c" GHG in the "y" process (tons of gas emitted per ton of MSW);

y: process type (landfill, composting, and gasification).

In order to calculate the total monetary value of the GHGs emitted, the following expression is used (Equation 10):

$$GV_{c,y} = \sum_{t=0}^{n} GH_{c,y,t}\,.\,GP_c \quad (10)$$

Where:

$GV_{c,y}$: Total monetary value of "c" GHG, emitted in "y" process;

GP_c: median price of "c" gas, per ton (US$).

In line with our scenarios, the difference between the amount of GHG emitted by landfill and by other technologies is given as (Equation 11):

$$GVD_t = \sum_{c=0}^{n} GV_{t,c,y=landfill} - \sum_{c=0}^{n} GV_{t,c,y-landfill} \quad (11)$$

Where:

GVD_t: Total difference in GHG values;

$GV_{t,c,y=landfill}$: Sum of the monetary value of all the "c" GHG emitted by landfill;

$GV_{t,c,v}$: Sum of the monetary value of all the "c" GHGs emitted by the new technologies per scenario.

Jobs: a social issue

The mean number of jobs generated over the lifetime of the landfill project and by new technologies (per scenario) was estimated through the following expression (Equation 12):

$$J_{y,t} = \sum_{t=0}^{n} M_{y,t}\,/t \quad (12)$$

Where:

$J_{y,t}$: Average annual number of workers; and

$M_{y,t}$: Direct job requirements.

Financial and environmental indicators

The formulas include the GHG values, although these values are disregarded for the scenarios only containing financial estimates (excluding the environment). The cash flow balance, adapted from Tham and Vélez-Pareja (2004), can be defined by Equation 13:

$$CF_t = C_t + GVD_t + \sum_{e=0}^{n} V_{e,t} - \sum_{y=0}^{n} Capex_{y,t} - \sum_{y=0}^{n} Opex_{y,t} \quad (13)$$

Where:

CF_t: Cash flow balance of the "y"process, time "t" ($);

$Capex_{y,t}$: Capital expenditure of the "*y*" process – investment in equipment, time "*t*";
$Opex_{y,t}$: Operational expenditure of the "*y*" process, time "*t*".

For the financial indicators and the CBA, the monetary values are calculated at the present value, that is, costs and benefits are discounted at an appropriate discount rate. This rate is selected according to the estimated financial market conditions over the project's lifetime.

In the financial analysis, it is necessary to discount the cash flow balance. To this end, NPV must be calculated, and the project is feasible if $NPV \geq 0$. Based on Abdelhady (2021), the NPV formula is (Equation 14):

$$NPV = \sum_{t=0}^{n} CF_t/(1+d)^t \quad (14)$$

Where:
NPV: Net Present Value (US$);
d: Discount rate.

Another key financial indicator is IRR. Based on the IRR, it is possible to compare different projects, where the project with the highest IRR has the highest return on capital, if $IRR > 0$. Therefore, if the project has an $IRR > 0$, then the project provides a positive financial return (higher than the discount rate), otherwise there is capital loss. The IRR formula adapted from Halder *et al.* (2016) is (Equation 15):

$$\left(\frac{CF_t}{(1+d)^t}\right)/(1+IRR)^t = 0 \quad (15)$$

Where:
IRR: Internal Rate of Return.

Based on Maghsoudi and Sadeghi (2020), the discounted payback period (DPB) is a key indicator that calculates the time period in which the accumulated cash flow balance is positive (Equation 16):

$$\sum_{t=1}^{y} [CFB_t/(1+d)^t] = 0 \quad (16)$$

where:
DPB_t: the minimum value of "y";
CFB_t: cash flow balance accumulated over period "t".

The final indicator is benefit-cost ratio (B/C). The project is feasible if $\frac{B}{C} \geq 1$, because at this point the benefits are greater than the costs. Adapted from Zheng *et al.* (2009), the B/C ratio is (Equation 17):

$$\frac{B}{C} = \left(\sum_{t=0}^{n} \frac{\left(C_t + GVD_t + \sum_{e=0}^{n} V_{e,t}\right)}{(1+d)^t}\right) / \sum_{y,t=0}^{n} \frac{\left(Capex_{y,t} + Opex_{y,t}\right)}{(1+d)^t} \quad (17)$$

On the right side of this formula, the benefits are presented in the numerator with the costs in the denominator.

Sensitivity analysis: the Monte Carlo method

The volume of MSW may change due to consumption habits and environmental education, while the future price of electrical energy, recyclables, and black organic matter may change because of supply and demand pressures. Further uncertainty refers to the investment required over the project's lifetime in relation to equipment prices (growth in the volume of MSW will require more equipment for the various processes).

The Monte Carlo methodology is well known and has been widely used in various analyses, including sensitivity analyses for investment projects. Without intending to list all the literature on the subject, some examples of the use of this methodology can be found in: You *et al.* (2016); Zang *et al.* (2018); Cardoso, Silva and Eusébio (2019); Pradhan *et al.* (2019); and Puig-Gamero *et al.* (2020).

In order to apply the Monte Carlo method, normal distribution was used to generate 10,000 simulations for 2 discrete time periods (over 15 years, the project timeline) because of the need to invest in equipment. The uncertainty associated with the Monte Carlo process was 5%.

Data

The authors are willing to provide the spreadsheet with the calculated data and parameters to the audience (e-mail requests). Our MSW processing parameters are based on technical data regarding the efficiency of the equipment, as described in the manufacturers' technical reports (Table 2).

The technical data for the gasification, segregation of recyclables, and composting processes are described in the references described in Table 2, especially in Tulio (2020). Nevertheless, the following aspects should be highlighted. The processing flow capacity of a gasification reactor is 12,485 t/year/reactor. It is assumed to operate for 24 hours a day, 30 days a month, for 12 months. The efficiency of the power generator is 32%, according to the technical characteristics of the equipment — data provided by IPK PYROFLEX (manufacturer of gasification reactors). Power generation also depends on the synthesis gas energy generated in the pyrolysis process.

The recyclable segregation plant has a capacity of 900,000 tons/year. The estimated operation was 16 hours per day, 26 days per month, for 12 months. The efficiency in the mechanized segregation of MSW was obtained by technical data provided by the company STADLER DO BRASIL LTDA, manufacturer and operator of equipment for mechanized separation of MSW, and depends on the type and composition of the MSW.

For the composting process, the "DANO" equipment was setup with cylinders of 3 meter in diameter and 35 meter in length. The organic matter processing capacity is 50 tons with a 3-day detention period. This is a rotating drum to accelerate the composting rate. The waste remains inside the biostabilizers for two to three days and is moved with a rotation speed of over 1.0 rpm. It is necessary to finish the composting in beds, keeping these materials in yards to reach the level of maturity acceptable for agricultural purposes. For the processing capability of a composting reactor (organic matter), 16 hours of labor per day was considered for 12 months, and each DANO cylinder had a capacity of 6 t/day.

For the estimates, the first investment (Capital Expenditure — CAPEX) required a 100% loan to be paid back over 120 months, with a 12-month grace period (according to the rules of the Brazilian public investment bank). All financial and MSW values are based on 2020 ($t_0 = 2020$).

Two alternatives were proposed for the financial projections of collection fees: The actual collection fee that families and companies pay for MSW processing; Willingness-To-Pay (WTP) — a 68.76% increase in the actual collection fee. This increase is based on a Willingness-To-Pay survey carried out within the CONRESOL area. The survey asked people what they considered to be a fair collection fee in order to implement more environmentally friendly MSW technologies (TULIO, 2020).

Landfill costs were estimated using values obtained from FGV (2007). These economic assessment data include information on costs from several landfill plants. Other values are shown in Table 3.

RESULTS AND DISCUSSION

The GHG emissions avoided in each scenario are presented in Table 4. Scenario 3 (gasification, recycling, and composting) avoided most GHG emissions. One can also see that scenario 2 avoids a higher volume of GHG emissions than scenario 1. Scenario 2 includes gasification and recycling, while scenario 1 only refers to gasification.

The setup with the highest number of combinations is therefore the one that avoids the most GHG emissions. The only exception to this is SO_x, since, according to Haraguchi, Siddiqi and Narayanamurti (2019), gasification emits more SO_x than landfills. The most avoided emissions are seen in scenario 3, and in relation to CO_2 and CH_4. Ninety-seven percent of CH_4 emissions are avoided, while for CO_2 this figure is 86%. However, with the exception of SO_x, the avoided emissions of the other gases fall between 83 and 97%. In scenario 1, less emissions are avoided than in the other scenarios; however, compared to landfills, this remains significant. In this scenario, for example, avoided CH_4 emissions are 97%, while those for CO_2 are 66%.

The estimated number of direct jobs is shown in Figure 3. In scenario 3, the number of jobs is 1,130, while in scenario 2 it is 935, in scenario 1 there are 804 jobs, and in the landfill there are 118 jobs. All these job numbers are for the average of the project period (30 years).

When comparing the scenarios with landfill, it is possible to observe that changing to new technologies increases the demand for jobs. This is because job requirements increase in order to meet the needs of each MSW processing plant. The number of jobs in Scenario 3 is approximately 10 times higher than for landfills, since it contains all the new technologies that require investment. In addition to the economic, financial, and environmental impacts, the change in MSW processing also generates social benefits by generating new jobs.

Table 2 – Parameters and sources.

Parameters	Value	Source
r = Population growth rate	0.57% (year)	Ipardes (2018)
Capex Loan Interest Rate (payment in 120 months)	8.35% (year)	BNDES (2020)
d = Discount Rate	7.8% (year)	Bacen (2020)
t = Project duration (useful life of landfill[1])	30 (Years)	Conresol (2018)
S_t = Collection fee	US$19.81 (by year charged for household or company)	Conresol (2020); Curitiba (2020)
M_{yt} = Job requirements	According to process type (units of jobs)	Brasil (2010); FIPE (2017); Ipk-piroflex (2019); Stadler (2019)
θ_Z = MSW segregation parameter of "*Z*" MSW	Based on waste volume by type (tons of MSW/tons of recyclables)	Conresol (2018)
β = Parameter for conversion of organic matter into black organic matter	0.26 (tons of organic matter/black organic matter)	Silva *et al.* (2005); Brasil (2010)
ε_Z = Energy production coefficient of "*Z*" MSW	0.824 (MW/ton)	Ipk-piroflex (2019)
Y_{cy} = emission coefficient of "*c*" GHG in "*y*" process	Based on process type (tons of gas emitted per ton of MSW)	Chang, Chen and Chang (1998); Beck-Friis *et al.* (2000); Gladding and Thurgood (2004); Komilis and Ham (2004); Lou and Nair (2009); Thorneloe (2012); Haraguchi, Siddiqi and Narayanamurti (2019); Thuppahige, Gheewala and Babel (2022)

[1]Biological landfill operation: base sealing, drainage and slurry treatment system, biogas drainage and flaring, and rainwater drainage.

Table 3 – Variables and sources.

Variables	Value	Source
W_t = Total volume of MSW for processing	822,072 (tons)	Conresol (2018)
P_0 = Actual population	3,498 (millions)	Ipardes (2018)
C_t = Total value paid to the MSW processing company - Actual Collection Fee	US$ 89 (millions)	Conresol (2018)
C_t = Total value paid to the MSW processing company - collection fee by WTP	US$ 150 (millions)	Tulio (2020)
W_Z = Total volume of "*Z*" MSW produced by P_0 population	Based on waste volume by type (tons)	Conresol (2018)
U_t = Quantity of electrical energy used by the MSW company facilities	Based on operational equipment (MW)	Silva *et al.* (2005); Brasil (2010); Ipk-piroflex (2019); Stadler (2019)
P_{et} = Price of "*e*" product (US$)	Based on product type ($)	Mfrural (2020); Sucatas (2020); Tradener (2020)
GP_c = median price of "*c*" gas, per ton (US$)	Based on type of gas ($)	Harder and Gibson (2011); Marten and Newbold (2012); Council (2013); Haraguchi, Siddiqi and Narayanamurti (2019)
$Capex_{yt}$ = Capital expenditure of the "*y*" process	Based on process type ($)	FGV (2007); Brasil (2010); Ipk-piroflex (2019); Stadler (2019)
$Opex_{yt}$ = Operational expenditure of the "*y*" process	Based on process type ($)	FGV (2007); Brasil (2010); Ipk-piroflex (2019); Stadler (2019)

The results for NPV and DPB according to scenario and type of collection fee can be found in Table 5. This table contains results that both include and exclude the benefits of avoiding GHG emissions. Where the avoided GHG are not included as benefits, a purely financial overview is provided. However, there is socioeconomic and environmental value to avoiding GHG. Furthermore, simulations were performed for two types of collection fee. The first is the Actual Collection Fee, while the second is based on WTP.

For the Actual Collection Fee (ACF), and excluding the benefits of avoiding GHG, the NPV for all the scenarios is negative, *i.e.*, there is no return on investment. However, if the benefits of avoiding GHG are included, the return in terms of NPV falls between US$186 and US$285 (million), depending on the scenario.

For the collection fee by WTP and excluding the benefits of GHG avoidance, the NPV falls between US$420 and US$482 (million). In this case, the return in scenario 1 is higher than in the other scenarios, and the return on investment is seen within approximately 4 years and 5 months. This result is very similar to the calculations in Scenario 3.

However, when the benefits of GHG avoidance are included, the socioeconomic and environmental return for NPV falls between $712 and $793 (million), depending on the scenario. In this case, the return is greater in scenario 3 than in the other scenarios, due to the greater avoidance of GHG emissions. For this scenario, the return on investment occurs within 2 years and 6 months.

For the ACF, and excluding the benefits of avoiding GHG, it is noteworthy that the socioeconomic and environmental return in scenario 3 is higher than in the other scenarios. This is because there is a greater volume of avoided GHG emissions. In this scenario, there is a return on financial investment within 4 years and 9 months.

IRR outcomes are shown in Figure 4; and it is negative in all the scenarios (excluding the benefits of GHG avoidance and the ACF). However, if the benefits of GHG avoidance are included, the IRR vary between 9.9 and 30.4% per year. The highest rate was calculated for Scenario 3.

On the other hand, for the scenarios by WTP and excluding avoidance of GHG emissions, the IRR falls between 25.7 and 44.6% per year. The highest rate is in Scenario 3, which involves the implementation of all the technologies. If avoidance of GHG emissions is included, IRR will fall between 56.6 and 96.0% per year. Scenario 3 also has the highest rate.

However, when GHG avoidance is included, the socioeconomic and environmental rate of return is higher than the financial IRR in scenario 1, between 17 and 36 percentage points; scenario 2, between 14 and 30 percentage points; and scenario 3, between 32 and 51.

As a result of the NPV, the IRR is negative in all the scenarios (excluding the benefits of GHG avoidance and the ACF). This is because there is no return on financial investment. With the GHG avoidance included, the IRR is more than double in the scenarios with WTP, but there is not much difference in the scenarios including the ACF.

These IRRs may seem very high; however, since the interest rates in the Brazilian economy have been quite high for many decades, the investment attractiveness rating is also high. In order to attract investors, it is therefore necessary to have a high financial return, which takes into account risk and other financial investments.

The estimated IRR for landfill is approximately 37% per year, meaning that IRR higher than this rate could be considered very high. In order to implement the new technologies in line with the scenarios, one can consider IRR close to

Table 4 – Average annual volumes of GHG emitted by landfill and GHG emissions avoided by scenario – tons.

Gases	Landfill	Scenario 1	Scenario 2	Scenario 3
NOx	642.6	-385.6	-416.3	-534.0
SO_x	50.1	35.9	25.6	-13.8
PM	50.1	-38.7	-40.1	-43.9
CO_2	283,507.1	-189,004.7	-200,287.5	-243,645.8
CH_4	18,900.5	-18,471.4	-18,522.7	-18,368.8

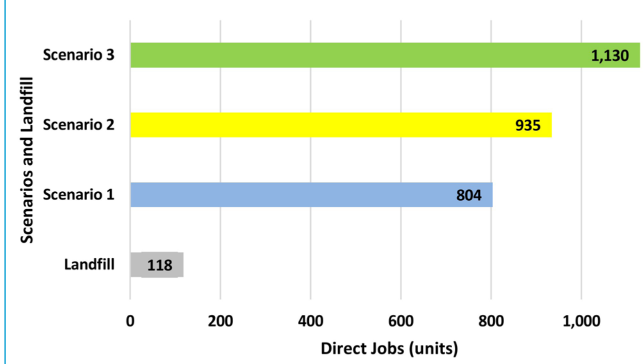

Figure 3 – Direct jobs (mean) by Scenario and Landfill.

Table 5 – Net Present Value (US$ million) and Discounted Payback by Scenario, Greenhouse Gases Avoidance Benefits and Type of Collection Fee.

Collection Fee Type	Scenario 1		Scenario 2		Scenario 3	
	NPV ($)	DPB (time)	NPV ($)	DPB (time)	NPV ($)	DPB (time)
Excluding Benefits of GHG avoidance						
Actual collection fee	-34.0	No Return	-105.7	No Return	-27.0	No Return
Willingness-To-Pay	482.7	4 years 5 m.	420.1	5 years 4 m.	480.4	3 years 8 m.
Including Benefits of GHG avoidance						
Actual collection fee	252.1	11 years 3 m.	186.7	14 years	285.7	4 years 6 m.
Willingness-To-Pay	768.8	2 years 10 m.	712.5	3 years 1 m.	793.0	2 years 6 m.

that of landfills to be sufficient. Since the scenarios that do not include GHG avoidance or the ACF have negative IRRs, and the scenarios with WTP and excluding GHG avoidance have IRRs between 25.7 and 44.6% per year (which is not very different from 37%), it makes sense to think that the estimated WTP is consistent with the projects' financial needs. For scenario 2, the collection fee could, perhaps, be a little higher.

Figure 5 shows the benefit/cost ratios for the scenarios, according to GHG avoidance and type of collection fee. In almost all the scenarios, the benefits outweigh the costs (B/C ratio greater than 1), with the exceptions being the scenarios that exclude the benefits of GHG avoidance and the ACF. In these scenarios, the costs outweigh the benefits (B/C ratio less than 1).

The highest benefit/cost ratio (1.76) is found in Scenario 3, including GHG avoidance and WTP. This means that the socioeconomic and environmental benefits outweigh the costs by approximately 75%. In all scenarios, including GHG avoidance and WTP, the benefit/cost ratio is greater than 1.5, that is, the benefits outweigh the costs by more than 50%.

If the B/C ratio were used to select the project with the best socioeconomic and environmental return, the result would be Scenario 3 with the WTP collection fee. This result is not surprising, since, compared to the other scenarios, the greatest volume of GHG emissions is avoided in Scenario 3, which also has the highest IRR, despite the greater need for investment (CAPEX and Operational Expenditure — OPEX). From a strictly environmental point of view, this also seems to be the most appropriate scenario. Scenario 3 provides evidence of the 3R principles through gasification, recycling, and composting.

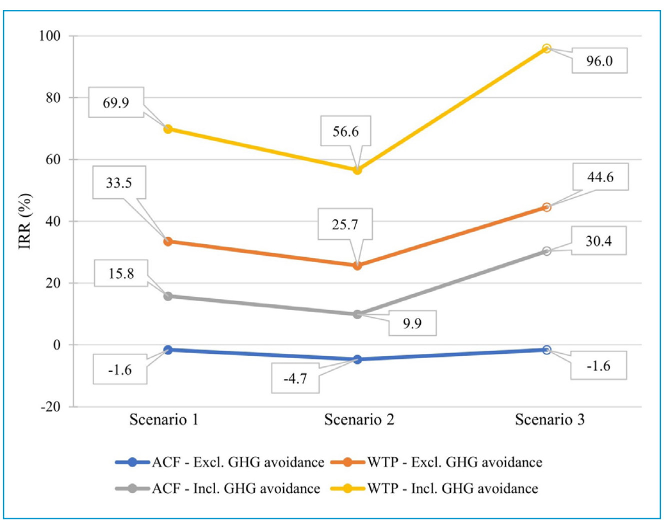

Figure 4 – IRR by Scenario, Type of Collection Fee and GHG avoidance.

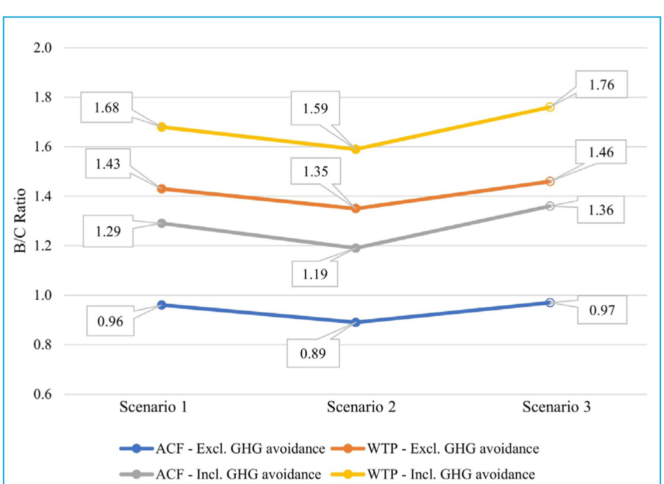

Figure 5 – Benefit Cost Ratio by Scenario, Collection Fee Type and GHG avoidance.

Sensitivity analysis

IRR results in the Monte Carlo simulations are shown in Figures 6 and 7, while those for the B/C ratio can be found in Table 5. In the scenarios assessed for

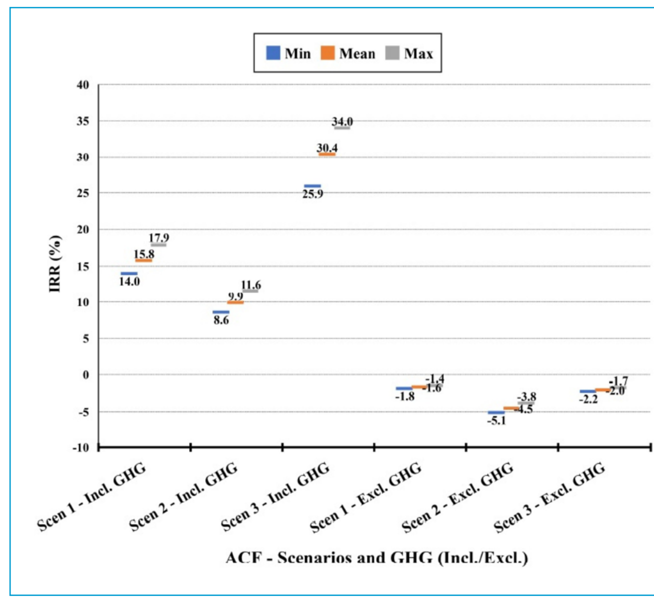

Figure 6 – Monte Carlo results for IRR and ACF (Actual Collection Fee) by Scenario and GHG avoidance.

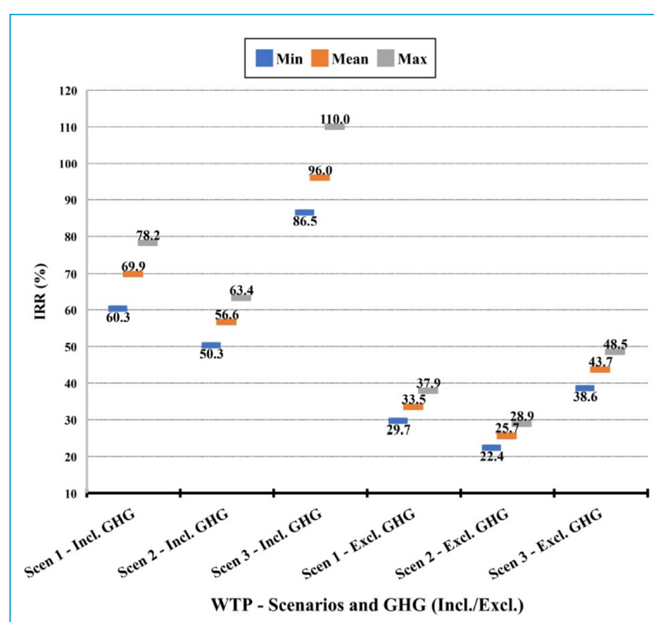

Figure 7 – Monte Carlo results for IRR and WTP (Willingness-To-Pay) by Scenario and GHG avoidance.

IRR by ACF, including and excluding GHG avoidance (Figure 6), the greatest difference between the maximum and minimum value is seen in Scenario 3, including GHG avoidance.

The same observations made in the ACF scenarios can be seen in IRR by WTP (Figure 6). However, under certain circumstances, Scenarios 1 and 2 (including the benefits of GHG avoidance) have similar returns, since the maximum value of Scenario 2 is greater than the minimum value of Scenario 1. In other words, Scenario 1 (gasification only) may have the same outcome as Scenario 2 (gasification and recycling). On the other hand, Scenario 3 has the highest return, since no other scenario has a return higher than its minimum value, which can also be observed in the ACF scenarios (Figure 6).

Overall, considering the 5% uncertainty associated with the Monte Carlo process, scenarios with higher returns (IRR) are subject to higher losses or gains, hence the greater difference between the maximum and minimum values.

The B/C ratio results of the Monte Carlo simulations (Table 6) provide the same conclusions as the IRR assessment. Scenario 3 by WTP and including GHG avoidance has the best benefit/cost ratio. However, under certain circumstances, Scenario 3 can produce the same B/C ratio as Scenarios 1. This ratio falls between the maximum and minimum values of Scenarios 2 and 3, respectively, and between the mean and minimum values of Scenario 3.

Limitations to assessing environmental effects

Some of the environmental and socioeconomic impacts that do not fall within the remit of this research, but which should be considered by policy makers, are:

- Changes related to natural resources: in the exploitation of natural resources as a result of the volume of recycled products; the production costs of using these inputs; and the benefits to industry and society from reduced pressure on natural resources;
- The impacts of reduced consumption of chemical fertilizers, due the supply of black organic matter;
- Increased real estate valuation in areas surrounding landfill locations, due to the eradication of harmful effects (smell, landscape, etc.);
- Benefits to the study area due to avoidance of GHG emissions.

Table 6 – Monte Carlo results for B/C ratio by scenario, type of collection fee and inclusion/exclusion of GHG avoidance.

	Scenarios	Min	Mean	Max
ACF - Excl. GHG avoidance	Scenario 1	0.95	0.96	0.97
	Scenario 2	0.87	0.89	0.90
	Scenario 3	0.96	0.97	0.98
WTP - Excl. GHG avoidance	Scenario 1	1.37	1.43	1.47
	Scenario 2	1.30	1.35	1.39
	Scenario 3	1.41	1.46	1.52
ACF - Incl. GHG avoidance	Scenario 1	1.25	1.29	1.33
	Scenario 2	1.17	1.19	1.22
	Scenario 3	1.31	1.36	1.40
WTP - Incl. GHG avoidance	Scenario 1	1.60	1.68	1.76
	Scenario 2	1.52	1.59	1.66
	Scenario 3	1.67	1.76	1.86

CONCLUSIONS

Our first conclusion concerns the ACF. Changes to implement any of the scenarios using new technologies are not feasible without subsidies from local governments. This is because financial results do not show a return on invested capital (in terms of IRR). The scenarios are only feasible within the scope of socioeconomic and environmental returns, that is, when the benefits from avoided GHG emissions are taken into account. This can also be seen in the B/C ratios, where the values are less than 1 if the benefits of the GHG avoidance are not included, and greater than 1 when they are. However, in addition to these returns, MSW treatment companies require financial results to ensure investment viability.

On the other hand, if WTP is taken into account in the scenarios, financial as well as socioeconomic and environmental feasibility is obtained (which includes avoided GHG emissions). In this case, Scenario 3 is the best one, since it generates a greater return in all senses. In restricted market situations, our sensitivity analysis demonstrated that the other scenarios may be equivalent, although this is unlikely.

These restricted or extreme situations may arise, for example, from:

- a price drop (in energy, recyclables, and black organic matter);
- a drop in the volume of MSW (which can occur through environmental education);
- a real increase in labor costs (an increase in wages higher than inflation);
- a real increase in equipment maintenance costs;
- a real increase in the cost of future investment (in order to increase MSW treatment over time).

Compared to the other scenarios, Scenario 3 is preferable in both financial and environmental terms, as it generates the highest return (NPV, payback, and IRR) and avoids more GHG emissions (in general). In terms of social benefits, this scenario also generates more jobs. In addition, this scenario is most consistent with the 3R principles.

If local governments were required to implement this scenario, it would involve wide-ranging public policies (economic, social, and environmental). However, for Scenario 3 to be a real possibility, the collection fee needs to increase. There is, therefore, a need for socioenvironmental awareness campaigns to convince the public to agree to such an increase. The population must be made aware of potential benefits. Another approach involves subsidies from local governments to implement the project. Regardless of how project implementation is facilitated, it is important to halt the disposal of MSW in landfill and to invest in more environmentally friendly activities that respect the environment, without neglecting other spheres of human development.

Future research

Future research is needed to improve the model's quantification of environmental effects on the urban and rural areas in which MSW treatment plants are located. This is especially important in relation to real estate valuation. On the other hand, it is necessary to quantify the local effects of avoiding GHG emissions. In parallel, it would be interesting to calculate the number of indirect jobs generated by a change in MSW treatment technology and the impacts on household income. This has an impact on those who pay the collection fee and on the workers at the MSW treatment company. The other benefits that ecologically friendly technologies can generate must be, therefore, incorporated. Another prominent issue concerns estimations of the impact that local government subsidies for the collection fee have on low--income households.

AUTHORS' CONTRIBUTIONS

Tulio, T.J.: Data curation, Formal analysis, Investigation, Writing – original draft. Schmitz, A.P.: Conceptualization, Methodology, Validation, Writing – review & editing.

REFERENCES

ABDALLAH, M.; SHANABLEH, M.; SHABIB, A.; ADGHIM, M. Financial feasibility of waste to energy strategies in the United Arab Emirates. *Waste Management*, v. 82, p. 207-219, 2018. https://doi.org/10.1016/j.wasman.2018.10.029

ABDELHADY, S. Performance and cost evaluation of solar dish power plant: Sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). *Renewable Energy*, v. 168, p. 332-342, 2021. https://doi.org/10.1016/j.renene.2020.12.074

AGBEJULE, A.; SHAMSUZZOHA, A.; LOTCHI, K.; RUTLEDGE, K. Application of Multi-Criteria Decision-Making Process to Select Waste-to-Energy Technology in Developing Countries: The Case of Ghana. *Sustainability*. v. 13, n. 22, p. 12863, 2021. https://doi.org/10.3390/su132212863

ALAM, P.; AHMADE, K. Impact of solid waste on health and the environment. *International Journal of Sustainable Development and Green Economics*, v. 2, n. 1, p. 165-168, 2013.

ARAFAT, H.A.; JIJAKLI, K.; AHSAN, A. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. *Journal of Cleaner Production*, v. 105, p. 233-240, 2015. https://doi.org/10.1016/j.jclepro.2013.11.071

ARRUDA, R.S.S. *Desenvolvimento de uma ferramenta para análise de dados de gerenciamento de RSU no Brasil e prospecção de oportunidades para recuperação energética. Universidade Federal de Santa Catarina*. Trabalho de Conclusão de Curso (Engenharia de Energia) – Araranguá, 2020.

ASTRUP, T.F.; TONINI, D.; TURCONI, R.; BOLDRIN, A. Life cycle assessment of thermal Waste-to-Energy technologies: review and recommendations. *Waste Management*, v. 37, p. 104-115, 2015. https://doi.org/10.1016/j.wasman.2014.06.011

AYODELE, T.R.; OGUNJUYIGBE, A.S.O.; ALAO, M.A. Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. *Applied Energy*, v. 201, p. 200-218, 2017. https://doi.org/10.1016/j.apenergy.2017.05.097

BANCO CENTRAL (BACEN). *Relatório de Inflação*. Brasília, v. 22, n. 1, 2020. 85 p.

BANCO NACIONAL DE DESENVOLVIMENTO ECONÔMICO E SOCIAL (BNDES). *TFB: Taxa Fixa do BNDES*. Banco Nacional de Desenvolvimento Econômico e Social. Available at: https://www.bndes.gov.br/wps/portal/site/home/financiamento/guia/custos-financeiros/tfb-taxa-fixa-bndes. Accessed on: Oct. 7, 2020.

BECK-FRIIS, B.; PELL, M.; SONESSON, U.; JÖNSSON, H.; KIRCHMANN, H. Formation and emission of N2O and CH4 from compost heaps of organic household waster. *Environmental Monitoring and Assessment*, v. 62, n. 3, p. 317-331, 2000. https://doi.org/10.1023/A:1006245227491

BIDONE, F.R.; POVINELLI, J. *Conceitos básicos de resíduos sólidos*. São Carlos: ed. EESC/USP, 1999. 120 p.

BRASIL. *Manual para implantação de compostagem e de coleta seletiva no âmbito de consórcios públicos*. Brasília: Ministério do Meio Ambiente, 2010. 69 p.

BUNDHOO, Z. Solid waste management in least developed countries: actual status and challenges faced. *Journal of Material Cycles and Waste Management*, v. 20, n. 3, p. 1867-1877, 2018. https://doi.org/10.1007/s10163-018-0728-3

BUTT, E.P.; MORSE, G.K.; GUY, J. A.; LESTER, J.N. Co-recycling of sludge and municipal solid waste: a cost-benefit analysis. *Environmental Technology*, v. 19, n. 12, p. 1163-1175, 1998. https://doi.org/10.1080/09593331908616777

CARDOSO, J.; SILVA, V.; EUSÉBIO, D. Techno-economic analysis of a biomass gasification power plant dealing with forestry residues blends for electricity production in Portugal. *Journal of Cleaner Production*, v. 212, p. 741-753, 2019. https://doi.org/10.1016/j.jclepro.2018.12.054

CASTALDI, M.J.; THEMELIS, N.J. The case for increasing the global capacity for waste to energy (WTE). *Waste and Biomass Valorization*, v. 1, n. 1, p. 91-105, 2010. https://doi.org/10.1007/s12649-010-9010-1

CHANG, N.B.; QI, C.; ISLAM, K.; HOSSAIN, F. Comparisons between global warming potential and cost-benefit criteria for optimal planning of a municipal solid waste management system. *Journal of Cleaner Production*, v. 20, n. 1, p. 1-13, 2012. https://doi.org/10.1016/j.jclepro.2011.08.017

CHANG, Y.H.; CHEN, W.C.; CHANG, N.B. Comparative evaluation of RDF and MSW incineration. *Journal of Hazardous Materials*, v. 58, n. 1-3, p. 33-45, 1998. https://doi.org/10.1016/S0304-3894(97)00118-0

CHEN, Y.T. A cost analysis of food waste composting in Taiwan. *Sustainability*. v. 8, n. 11, p. 1210-1223, 2016. https://doi.org/10.3390/su8111210

CHOWDHURY, A.H.; MOHAMMAD, N.; HAQUE, R.U.; HOSSAIN, T. Developing 3Rs (reduce, reuse and recycle) strategy for waste management in the urban areas of Bangladesh: Socioeconomic and climate adoption mitigation option. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, v. 8, n. 5, p. 9-18, 2014. https://doi.org/10.9790/2402-08510918

CHRISTENSEN, T. *Solid waste technology and management*. Chichester: John Wiley & Sons, 2011. 2 v. 1056 p.

CONSÓRCIO INTERMUNICIPAL PARA GESTÃO DOS RESÍDUOS SÓLIDOS URBANOS (CONRESOL). *Estudo de Viabilidade Técnica e Econômico-Financeira (EVTE)*. Curitiba: Conresol, 2020. 120 p.

CONSÓRCIO INTERMUNICIPAL PARA GESTÃO DOS RESÍDUOS SÓLIDOS URBANOS (CONRESOL). *Plano de gerenciamento do tratamento e destinação de resíduos sólidos urbanos*. Curitiba: Conresol, 2018. 40 p.

COUNCIL, D.P. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Technical Support Document. Interagency Working Group on Social Cost of Carbon, United States Government. Washington D.C.: Environmental Protection Agency, 2013. 35 p.

CURITIBA. *Planejamento, finanças e orçamento – Tabela do IPTU*. Prefeitura de Curitiba. Available at: https://www.curitiba.pr.gov.br/conteudo/tabela-do-iptu/368. Accessed on: Jan. 21, 2020.

DAMANHURI, E.; WAHYU, I.M.; RAMANG, R.; PADMI, T. Evaluation of municipal solid waste flow in the Bandung metropolitan area, Indonesia. *Journal of Material Cycles and Waste Management*, v. 11, n. 3, p. 270-276, 2009. https://doi.org/10.1007/s10163-009-0241-9

DONG, J.; TANG, Y.; NZIHOU, A.; CHI, Y.; WEISS-HORTALA, E.; NI, M.; ZHOU, Z. Comparison of waste-to-energy technologies of gasification and incineration using life cycle assessment: Case studies in Finland, France and China. *Journal of Cleaner Production*, v. 203, p. 287-300, 2018. https://doi.org/10.1016/j.jclepro.2018.08.139

ELSAID, S.; AGHEZZAF, E.H. Designing a Sustainable Waste Management System: The Strategic Planning Model and Related Sustainability Issues. *In*: INTERNATIONAL CONFERENCE ON INFORMATION SYSTEMS, LOGISTICS AND SUPPLY CHAIN, 6., 2016. *Annals*... Bordeaux: ILS Conference, 2016. p. 1-14.

FUNDAÇÃO GETULIO VARGAS (FGV). *Estudo técnico sobre os aspectos econômicos e financeiros da implantação e operação de aterros sanitários*. Technical report. Rio de Janeiro: FGV Projetos/ABETRE, 2007. 52 p.

FUNDAÇÃO INSTITUTO DE PESQUISAS ECONÔMICAS (FIPE). *Aspectos técnicos/econômico-financeiros da implantação, manutenção, operação e encerramento de aterros sanitários*. Technical report. São Paulo: Fundação Instituto de Pesquisas Econômicas, 2017. 75 p.

GARDNER, G. *State of the World*. Washington, D.C.: Island Press, 2016.

GLADDING, T.; THURGOOD, M. *Review of Environmental and Health Effects of Waste Mangement:* Municipal Solid Waste and Similar Wastes. London: Department for Environment Food and Rural Affairs, 2004. 420 p.

GOHLKE, O.; MARTIN, J. Drivers for innovation in waste-to-energy technology. *Waste Management & Research*, v. 25, n. 3, p. 214-219, 2007. https://doi.org/10.1177/0734242X07079146

GORDON, R.B.; BERTRAM, M.; GRAEDEL, T.E. Metal stocks and sustainability. *Proceedings of the National Academy of Sciences*, v. 103, n. 5, p. 1209-1214, 2006. https://doi.org/10.1073/pnas.0509498103

HADIDI, L.A.; OMER, M.M. A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia. *Waste Management*, v. 59, p. 90-101, 2017. https://doi.org/10.1016/j.wasman.2016.09.030

HALDER, P.K.; PAUL, N.; JOARDDER, M.U.H.; KHAN, M.Z.H.; SARKER, M. Feasibility analysis of implementing anaerobic digestion as a potential energy source in Bangladesh. *Renewable and Sustainable Energy Reviews*, v. 65, p. 124-134, 2016. https://doi.org/10.1016/j.rser.2016.06.094

HARAGUCHI, M.; SIDDIQI, A.; NARAYANAMURTI, V. Stochastic cost-benefit analysis of urban waste-to-energy systems. *Journal of Cleaner Production*, v. 224, p. 751-765, 2019. https://doi.org/10.1016/j.jclepro.2019.03.099

HARDER, E.; GIBSON, J.M. The costs and benefits of large-scale solar photovoltaicpower production in Abu Dhabi, United Arab Emirates. *Renewable Energy*, v. 36, n. 2, p. 789-796, 2011. https://doi.org/10.1016/j.renene.2010.08.006

INSTITUTO PARANAENSE DE DESENVOLVIMENTO ECONÔMICO E SOCIAL (IPARDES). *Projeção da população dos municípios do Paraná para o período 2018 a 2040*. Technical report. Curitiba: Instituto Paranaense de Desenvolvimento Econômico e Social, 2018. 15 p.

IPK-PIROFLEX. *Documentos*. Available at: http://w2ebioenergia.com.br/documentos/?lang=. Accessed on: Sept. 23, 2019.

KOMILIS, D.P.; HAM, R.K. Life-cycle inventory of municipal solid waste and yard waste windrow composting in the United States. *Journal of Environmental Engineering*, v. 130, n. 11, p. 1390-1400, 2004. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:11(1390)

KOPNINA, H. Revisiting education for sustainable development (ESD): Examining anthropocentric bias through the transition of environmental education to ESD. *Sustainable Development*, v. 22, n. 2, p. 73-83, 2014. https://doi.org/10.1002/sd.529

LEITE, M.B.F.; SILVA, G.H.J.; SOUZA, L.F. Modelos matemáticos para o crescimento da população do estado de São Paulo e a exploração de diferentes taxas de crescimento. *Ciência & Educação*, v. 17, n. 4, p. 927-940, 2011. https://doi.org/10.1590/S1516-73132011000400010

LIU, T.; REN, X.; ZHAO, J.; CHEN, H.; WANG, Q.; AWASTHI, S.K.; DUAN, Y.; PANDEY, A.; TAHERZADEH, M.J.; AWASTHI, M.K.; ZHANG, Z. Sustainability analysis of large-scale food waste composting. In: *Actual Developments in Biotechnology and Bioengineering*. Amsterdam: Elsevier, 2020. p. 301-322. https://doi.org/10.1016/B978-0-444-64309-4.00013-1

LOMBARDI, L.; CARNEVALE, E.; CORTI, A. A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Management*, v. 37, p. 26-44, 2015. https://doi.org/10.1016/j.wasman.2014.11.010

LOU, X.F.; NAIR, J. The impact of landfilling and composting on greenhouse gas emissions–a review. *Bioresource Technology*, v. 100, n. 16, p. 3792-3798, 2009. https://doi.org/10.1016/j.biortech.2008.12.006

LUDWIG, C.; HELLWEG, S.; STUCKI, S. (eds.). *Municipal solid waste management:* strategies and technologies for sustainable solutions. Berlin/Heidelberg: Springer Science & Business Media, 2012. 534 p. https://doi.org/10.1007/978-3-642-55636-4

MABALANE, P.N.; OBOIRIEN, B.O.; SADIKU, E.R.; MASUKUME, M. A techno-economic analysis of anaerobic digestion and gasification hybrid system: energy recovery from municipal solid waste in South Africa. *Waste and Biomass Valorization*, v. 12, n. 3, p. 1167-1184, 2021. https://doi.org/10.1007/s12649-020-01043-z

MAGHSOUDI, P.; SADEGHI, S. A novel economic analysis and multi-objective optimization of a 200-kW recuperated micro gas turbine considering cycle thermal efficiency and discounted payback period. *Applied Thermal Engineering*, v. 166, p. 114644-114656, 2020. https://doi.org/10.1016/j.applthermaleng.2019.114644

MALINAUSKAITE, J.; JOUHARA, H.; CZAJCZYNSKA, D.; STANCHEV, P.; KATSOU, E.; ROSTKOWSKI, P.; THORNE, R.J.; COLÓN, J.; PONSÁ, S.; AL-MANSOUR, F.; ANGUILANO, L.; KRZYZYNSKA, R.; LÓPEZ, I.C.; VLASOPOULOS, A.; SPENCER, N. Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. *Energy*, v. 141, p. 2013-2044, 2017. https://doi.org/10.1016/j.energy.2017.11.128

MARTEN, A.L.; NEWBOLD, S.C. Estimating the social cost of non-CO2GHG emissions: methane and nitrous oxide. *Energy Policy*, v. 51, p. 957-972, 2012. https://doi.org/10.1016/j.enpol.2012.09.073

MCCREA, M.; TAN, T.K.; TING, H.H.; ZUO, X. *A cost-benefit analysis of different waste-to-energy technologies for the management of municipal solid waste in Singapore*. Working paper 26800. Chicago: University of Chicago, 2009. 25 p.

MEDINA, M. *Solid wastes, poverty and the environment in developing country cities:* Challenges and opportunities. WIDER Working Paper 2010/23. Helsinki: United Nations University World Institute for Development Economics Research, 2010. 15 p.

MELO, F.H.F.A. *Caracterização e estudo do gerenciamento dos resíduos sólidos urbanos em um consórcio municipal do Estado de Pernambuco*. Master Thesis (Master program in environmental and civil engineer) – Universidade Federal de Pernambuco, Caruaru, 2015. 107 p.

MENEZES NETO, J.T.; DOMINGUES, E.G.; CARVALHAES, V.; ALVES, A.J. Análise de viabilidade técnica e econômica da tecnologia de gaseificação como alternativa para geração de energia elétrica a partir de resíduos sólidos urbanos. *Gestão & Produção*, v. 28, n. 4, 2021. https://doi.org/10.1590/1806-9649-2021v28e5756

MFRURAL. *Busca*. Available at: https://www.mfrural.com.br/busca/adubo-organico-granel/estado/parana/cidade/curitiba. Accessed on: Aug. 21, 2020.

MURRAY, R. *Creating wealth from waste*. London: Demos, 1999. 167 p.

NG, W.P.Q.; LAM, H.L.; VARBANOV, P.S.; KLEMES, J.J. Waste-to-energy (WTE) network synthesis for municipal solid waste (MSW). *Energy Conversion and Management*, v. 85, p. 866-874, 2014. https://doi.org/10.1016/j.enconman.2014.01.004

PARSHALL, L.; HARAGUCHI, M.; ROSENZWEIG, C.; HAMMER, S.A. *The contribution of urban areas to climate change:* New York City case study. Unpublished case study prepared for the Global Report on Human Settlements, 2011. 20 p.

PRADHAN, P.; GADKARI, P.; MAHAJANI, S.M.; ARORA, A. A conceptual framework and techno-economic analysis of a pelletization-gasification based bioenergy system. *Applied Energy*, v. 249, p. 1-13, 2019. https://doi.org/10.1016/j.apenergy.2019.04.129

PUIG-GAMERO, M.; TRAPERO, J. R.; SÁNCHEZ, P.; SANCHEZ-SILVA, L. Is methanol synthesis from co-gasification of olive pomace and petcoke economically feasible? *Fuel*, v. 278, 118284, 2020. https://doi.org/10.1016/j.fuel.2020.118284

RAHMAN, S.M.S.; AZEEM, A.; AHAMMED, F. Selection of an appropriate waste-to-energy conversion technology for Dhaka City, Bangladesh. *International Journal of Sustainable Engineering*, v. 10, n. 2, p. 99-104, 2017. https://doi.org/10.1080/19397038.2016.1270368

REIS, M.F.P. *Avaliação do processo de compostagem de resíduos sólidos urbanos*. PhD (Dissertation) – Programa de Pós-Graduação em Engenharia dos Recursos Hídricos e Saneamento Ambiental, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2005. 239 p.

SHARMA, B.K.; CHANDEL, M.K. Life cycle cost analysis of municipal solid waste management scenarios for Mumbai, India. *Waste Management*, v. 124, p. 293-302, 2021. https://doi.org/10.1016/j.wasman.2021.02.002

SILVA, F.C.; CHITOLINA, J.C.; BALLESTERO, S.D.; VOIGTEL, S.D.S; MELO, J.R.B. Processos de produção de compostos de lixo e a sua qualidade como fertilizante orgânico. *Holos Environment*, v. 5, n. 2, p. 121-136, 2005. https://doi.org/10.14295/holos.v5i2.317

SMITH, R.L.; SENGUPTA, D.; TAKKELLAPATI, S.; LEE, C.C. An industrial ecology approach to municipal solid waste management: II. Case studies for recovering energy from the organic fraction of MSW. *Resources, Conservation and Recycling*, v. 104, part A, p. 317-326, 2015. https://doi.org/10.1016/j.resconrec.2015.05.016

SONG, Q.; WANG, Z., LI, J. Environmental performance of municipal solid waste strategies based on LCA method: a case study of Macau. *Journal of Cleaner Production*, v. 57, p. 92-100, 2013. https://doi.org/10.1016/j.jclepro.2013.04.042

SRIWANNAWIT, P.; ANISA, P.A.; RONY, A.M. Policy impact on economic viability of biomass gasification systems in Indonesia. *Journal of Sustainable Development of Energy, Water and Environment Systems*, v. 4, n. 1, p. 56-68, 2016. https://doi.org/10.13044/j.sdewes.2016.04.0006

STADLER. *Instalação de classificação de Resíduos Sólidos Urbanos*. Available at: https://www.yumpu.com/pt/document/view/16396985/instalacao-de-classificacao-de-residuos-solidos-urbanos-stadler-. Accessed on: June 23, 2019.

SUCATAS. *Tabela Nacional Média de Produtos Recicláveis*. Available at: http://sucatas.com/portal/pages/internas/Tabela-Nacional-de-Precos-0. Accessed on Feb. 10, 2020.

SUN, Y.; QIN, Z.; TANG, Y.; HUANG, T.; DING, S.; MA, X. Techno-environmental-economic evaluation on municipal solid waste (MSW) to power/fuel by gasification-based and incineration-based routes. *Journal of Environmental Chemical Engineering*, v. 9, n. 5, 106108, 2021. https://doi.org/10.1016/j.jece.2021.106108

THAM, J.; VÉLEZ-PAREJA, I. *Principles of cash flow valuation:* An integrated market-based approach. Burlington: Elsevier, 2004. 487 p.

THORNELOE, S. *State of practice for emerging waste conversion technologies*. Washington, D.C.: Environmental Protection Agency, 2012. 80 p.

THUPPAHIGE, R.T.W.; GHEEWALA, S.H.; BABEL, S. Environmental impact of organic fraction of municipal solid waste treatment by composting in Sri Lanka. *Journal of Material Cycles and Waste Management*, v. 24, p. 189-199, 2022. https://doi.org/10.1007/s10163-021-01305-5

TILBURY, D. Environmental education for sustainability: A force for change in higher education. *In: Higher education and the challenge of sustainability*. Dordrecht: Springer, 2004. p. 97-112. https://doi.org/10.1007/0-306-48515-X_9

TRADENER. *Comercialização*. Available at: https://tradener.com.br/solucoes/. Accessed on: Feb. 20, 2020.

TULIO, T.J. *Análise custo-benefício da mudança de tecnologia no tratamento dos RSU: um estudo para a área do Conresol*. Master (Thesis) – Degree Program in urban and industrial environment, Universidade Federal do Paraná, Curitiba, 2020. 205 p.

UNITED NATIONS DEVELOPMENT PROGRAM (PNUD). *Atlas do desenvolvimento Humano*. Municípios. PNUD, 2010. Available at: http://www.atlasbrasil.org.br/consulta. Accessed on: Apr. 1, 2023.

YOU, S.; WANG, W.; DAI, Y.; TONG, Y.W.; WANG, C.H. Comparison of the co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification-and incineration-based waste treatment schemes. *Bioresource Technology*, v. 218, p. 595-605, 2016. https://doi.org/10.1016/j.biortech.2016.07.017

ZANG, G.; JIA, J.; TEJASVI, S.; RATNER, A.; LORA, E.S. Techno-economic comparative analysis of biomass integrated gasification combined cycles with and without CO2 capture. *International Journal of Greenhouse Gas Control*, v. 78, p. 73-84, 2018. https://doi.org/10.1016/j.ijggc.2018.07.023

ZHENG, W.; SHI, H.; CHEN, S.; ZHU, M. Benefit and cost analysis of mariculture based on ecosystem services. *Ecological Economics*, v. 68, n. 6, p. 1626-1632, 2009. https://doi.org/10.1016/j.ecolecon.2007.12.005