Using life cycle assessment to compare efficiency and environmental impacts of different waste to energy options for Sao Paulo's municipal solid waste

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Abstract

While Brazilian municipal solid waste (MSW) is most often collected and disposed of at "controlled" dumps and landfills, a large amount of refuse still ends up at irregular dumping sites. Unfortunately, there are few cases where waste is processed in a manner that provides additional benefits to local communities, for example, recovering energy from waste. The most common form of energy recovery practiced worldwide is converting it to electricity. In order to meet current energy needs and reduce fossil fuel emissions, this approach is a crucial component of any regional energy strategy and therefore should be considered wherever applicable. The present study quantified the feasibility of implementing alternative and complementary technologies for treatment and final disposal of the MSW of São Paulo to generate electricity with consideration of potential environmental impacts using life cycle assessment (LCA). The technologies considered were (i) disposal at landfill with biogas recovery, (ii) mechanical biological treatment and (iii) incineration. The program SimaPro 7.3.3 was used to analyse the life cycle impact (LCI) and life cycle impact assessment (LCIA).

The scope of the study, including the border and the detailing, was defined based on the technological treatment and disposal routes for MSW.. Results showed that, among the alternatives considered in this study, the electricity generated from the combined processes of a mechanical biological treatment system and incineration is the most attractive option in terms of minimizing the environmental impacts. Electricity generation from incineration process proved to be attractive not only in terms of environmental impacts, but also in terms of energy efficiency, yielding more energy than simply collecting biogas from landfill. Results were classified in terms of potential long-term impacts, i.e., considering the potential environmental impacts over a period of 100 years. When considering long-term impacts, the greatest areas of concern were regarding carcinogenic substances, non-carcinogenic substances, ecotoxicity, and eutrophication.

As a general conclusion, this study identifies current options and opportunities for Brazil, for the implementation of projects related to energy convertion from MSW, with a focus on the incineration process, with the caveat that there are still socio-political-economic barriers to the latter process, despite its environmental benefits and energy efficiency.

Keywords: municipal solid waste; energy; biogas; incineration; life cycle assessment

Introduction

According to ABRELPE [1], 58.0% of Brazil's MSW is sent to landfills, especially in large cities. The remainder is sent to controlled landfills (24.2%), or dumps (17.8%), present in most small and medium-sized cities.

According to Campos [2], on an average, the generation of waste per capita in Brazil is 0.96 kg / day. With the trend in growth of the national economy, it is expected that these values will increase in coming years. There will only be an increasing need for stricter policies for regulating landfill conditions and greater economic incentive for the conversion of MSW into energy. Since 2010, the National Policy on Solid Waste (PNRS) has been promoting and encouraging new technologies for the treatment, disposal, and utilization of MSW throughout the country in anticipation of the increase in MSW.

Already implemented in many parts of the world, MSW is viewed as a resource for the generation of electricity. Technology varies, which is why different processes and energy systems should be studied and evaluated with consideration of energy yield and environmental impacts. It is important that investors and decision-makers obtain consistent information for analysis, projection, and implementation of the most suitable and sustainable technologies for MSW management and its energy use.

With a long-term perspective, the National Energy Plan 2030 [3] predicts the possibility of generating up to 1,300 MW in the next 25 years from power plants using MSW: an indication of what is expected from the progress of energy derived from urban waste. Because of the obvious environmental, health, and social benefits, market demand has resulted in the advancements in MSW energy recovery, and there are a number of available sophisticated options.

Selecting the best system, however, requires assessing outcomes and impacts. Management tools have been created in order to assist organizations in evaluating technology in relation to environmental impacts and benefits. Among them, the emergence of a concept of life cycle assessment (LCA), which provides a technique for evaluating the environmental performance over entire life cycles of a product or process. According to Silva and Kulay [4], in the case of an evaluation methodology where the focus lies on the function of the product or process, LCA provides information about the interactions that occur between the steps that make up the life cycle and the environment. Because of this, it is possible to distinguish between applications that are designed for LCA in two ways:

- comparison of the environmental performance of products or processes that fulfil the same function; and
- identification of opportunities to improve environmental performance.

With this perspective, LCA was chosen as the methodology for evaluating the environmental performance of the different technologies for electricity generation from MSW, given that this method considers the entire production chain of processes and the different environmental impacts created by them.

Objective

The objective of this work is to evaluate and compare the environmental performance of treatment and disposal processes of MSW, using the CTR-Caieiras (a landfill and waste centre) as a case study. Employing the LCA approach, three technologies will be evaluated regarding their potential as a source of electricity: landfill biogas collection, accelerated anaerobic digestion, and incineration.

Municipal solid waste management in Brazil

According to the Brazilian Constitution of 1988 [5], MSW is the property and responsibility of municipal governments, who must ensure its proper collection and disposal.

The PNRS, which had been pending in Congress from 1991 for almost 20 years, was enacted in August 2010; it aims to not only regulate the proper management of solid waste, but promote ways to reduce it. However, in order to conform to PNRS policy objectives, federal, state and municipal regulations need to be immediately implemented.

Common in Brazil, landfills have been the predominant choice for waste disposal due to their low cost and the country's land availability. Their seemingly low cost, however, has been misleading and the lack of financial resources has led to inadequate landfill operation practices between regions, leading to management failures and system inefficiencies. Consequently, the country's controlled landfills and dumps are potential sources of high pollution.

Incineration, has up until now, been seldom used in Brazil, as it requires higher operation costs in order to dispose of hazardous wastes.

Higher operation costs mean that Brazil is still far behind with regard to MSW disposal, and also continues to lag behind in environmental, economic, and social impacts associated with MSW, when compared to developed countries.

The current system's inefficiency, coupled with a lack of commitment from the public administration, paints not only an alarming picture regarding future environmental impacts, especially if MSW increases as is predicted, but also a loss of opportunity to create viable alternatives for treatment and energy recovery.

Reuse of energy from municipal solid waste

Biogas from landfills

A landfill can be defined as a place for disposing of MSW wherein the waste is safely enclosed, and is covered with soil, according to the criteria of engineering and operational procedures, in order to reduce environmental impacts, and thereby also protecting public health. They have lower environmental impacts compared to dumps and controlled landfills.

Landfills with waterproofing systems, such as landfill caps, were first implemented in Brazil in the 1990s: pioneer projects using this technique were the São João and Bandeirantes landfills in the city of São Paulo [6].

Landfill caps prevent biogases, such as methane, from escaping from the landfill into the atmosphere, and once captured can be used to generate electricity. In general, the capture and use of biogas has the following advantages: reduction of greenhouse gases; use for power generation or as fuel; and additional revenue for existing landfills (energy + carbon credits).

There are, however, also disadvantages: gas recovery isn't 100%, especially those landfills where construction was not intended for this purpose, maximum recovery is often limited to 50%; and gas utilization plants are very costly, due to the necessary treatment, uncertainty and change in biogas generation rates, and the decrease in the fuel availability over the course of the life of the project.

Biogas can be used as low, medium or high quality fuel, or when unused, it is recommended it be burnt as methane (main component) into the atmosphere, as it is much more combustible than CO_2. The most common uses for biogas are as fuel for turbines, gas engines, and boilers to produce electricity and even fuel cells as a source of energy. It can also be used for home heating or as a heat source for industrial processes. Additionally, it can also be purified by increasing the concentration of methane and used as fuel for transport vehicles or distributed through a natural gas pipeline. Biogas collected and converted from landfills employs the simplest technology for MSW energy recovery.

Anaerobic decomposition of organic materials in MSW occurs when microorganisms convert waste into more stable substances. The organic fractions of MSW consists of carbon dioxide (CO2), water, methane (CH4), hydrogen sulfide (H2S), mercaptans and other components (NMOCs - non methane organic compounds - organic compounds methane).

According to Bogner [7], the generation of gas occurs in four phases, which are characteristic of the useful life of a landfill:

- aerobic phase: CO_2 is produced, however, because of the high N_2 content, it declines in the passages for the 2nd and 3rd stages;
- O_2 depletion: results in an anaerobic environment with large amounts of CO_2 and some H_2S;
- anaerobic phase: CH_4 production starts and there is a reduction in the amount of CO_2 produced; and
- final stage: almost stable production of CH_4, CO_2, and N_2.

The landfill conditions, such as waste composition, cover material, project specifics, and the anaerobic state all determine the duration of the phases and gas generation, which may also vary depending on local climatic conditions.

Waste accumulation correlates with biogas production, and the longer waste is accumulated, the longer gas is produced, however, once waste depositing ceases, gas production goes into a sharp decline depending on the composition of the deposited waste.

The economic benefits of gas recovery for power generation is limited to a relatively short amount of time (between 12 and 18 years) compared to the duration of emissions as a whole. Even during this period, not all of the gas produced can be used for energy conversion due to cost inefficiencies of power generating units.

Biogas Production by Means of Anaerobic digestion

According to Verma [8], accelerated anaerobic digestion (AAD) can be defined as the conversion of organic material to carbon dioxide and methane through bacterial digestion in an oxygen-deficient atmosphere. This process is the same as the one that occurs in a landfill, but it is accelerated through equipment designed to optimize the conditions of the reaction in order to increase its speed. Besides methane and carbon dioxide, the gas or “biogas”, obtained during anaerobic digestion includes inert gases and some sulphur compounds. Anaerobic digestion is the result of a series of metabolic interactions with the performance of different groups of microorganisms. Methane production occurs in a wide range of temperatures, but increases significantly within the two bands: mesophilic - 25-40 ° C and thermophilic - 50-65 ° C.

The majority of anaerobic digestion systems require a pre-treatment prior to inputting the load, at which point non-digestible residues are separated and extracted. The separation ensures the removal of recyclable materials such as glass, metals, and hazardous waste. Within the digester, the load is diluted to achieve the desired solid-to-liquid ratio content and it remains there during the assigned retention time (about 20 days). For dilution, a wide variety of water sources can be used such as clean water, sewage, or liquid effluent recirculating inside the digester. A heat exchanger is often required to maintain the temperature within the digestion vessel. Biogas impurities are removed so that the product conforms to the needs of its application. In the case of waste treatment, the effluent from the digester is dehydrated and the liquid is recycled, used in the dilution of future feedstock. Bio-solids are aerobically treated in order to stabilize them for landfill or used as fuel for incineration [8].

According to Nichols [9], the amount of biogas produced depends, among other factors, the technology used in digestion. The typical composition of the biogas produced thereby is presented in Table 1.

Table 1. Typical composition of biogas.

Biogas	**COMPOSITION**
CH_4	55 - 70% volume
CO_2	30 - 45% volume
H_2S	200 - 4.000 ppm volume
Biogas heat value	20 - 25 MJ/Nm3
Energy in CH_4 (t RSU)	167 - 373 MJ/t RSU

[8].

Just as with recovered landfill gas, biogas from AAD can be consumed directly, in which case, it presents a calorific value between 19 and 25 MJ / Nm3, or it can be treated for separation and the methane, which has a calorific value similar to natural gas, can be used or distributed for heating. In terms of electricity generation, when using a 35% cogeneration engine, thermal energy can be converted to electrical energy, generating 50—150 kWh per ton of MSW, depending on the energy content of the waste.

The Incineration Process

Waste-to-energy (WTE) plants use incinerated MSW to produce steam to drive a turbine coupled to a generator that will generate electricity or be used directly in industrial processes (or heating). The process of electricity generation by MSW incineration is similar to conventional thermal plants based on the Rankine cycle, with the generation capacity depending directly on the heat of transformation efficiency in electricity and the calorific value of the incinerated material.

Although the classification in the heat value (PCI) should not be considered definitive in establishing the allocation of MSW, in Themelis [10] it is considered that:

- for PCI < 7,000 kJ / kg, incineration is not technically feasible (in addition to technical difficulties, it still requires the addition of auxiliary fuel);
- to obtain 7000 kJ / kg <PCI < 8400 kJ / kg, the technical feasibility of incineration still depends on some kind of pre-treatment that increases the calorific value; and
- for PCI> 8400 kJ / kg, gross burning ("mass burning") is technically feasible.

Incineration plants can generate between 400 and 700 kWh per ton of MSW. The dominant technology is known as "mass burning" in which waste is incinerated as it arrives, without pre-treatment or processing. There are no MSW incineration plants with energy recovery on a commercial scale in Brazil, although there are at least three on-going projects.

WTE conversion to electricity is relatively low in efficiency, between 20 and 25%, a result of restrictions on operating these plants at very high temperatures. Indeed, with the current state of technology, temperatures for burning waste materials should not exceed 450 ° C, to prevent corrosion of equipment.

The advantages of incinerators include:

- direct use of thermal energy to generate steam and/or electricity;
- continuous processing of waste supply;
- emits little noise and is odourless; and
- requires a small area for installation.

Disadvantages are:

- excessive moisture affects the combustion;
- necessity of using auxiliary fuel to support combustion;
- toxic metals can remain concentrated in the ashes; and
- high initial investment, operation, and maintenance costs.

Brazil generates on average 192,000 t / day of MSW. When applying the data provided by Campos [2], if this waste were incinerated, considering an average value of 0.5 MWh / t, it would be possible to obtain 35 TWh / year. With the right conditions, this value could be increased up to 0.7 MWh / t, or be 50 TWh / year.

Table 2. Incineration energy recovery potential.

Item	**Amount**	**Unit**	**Reference**
(a) MSW	59,07	M t/ano	(IBGE 2000)
(b) Energy factor	523,0	kWh / t MSW	(EPA 2002)
(c) Energy factor	769,2	kWh / t MSW	(TOLMASQUIM 2003)
(d) Energy factor	500.0	kWh / t MSW	(MENEZES 2000)
Calculated Energy (a x b)	30,89	TWh / year	
Calculated Energy (a x c)	45,44	TWh / year	
Calculated Energy (a x d)	30.0	TWh / year	

Source: [11]

LCA: concepts and use of technology choice for setting in MSW

The application of LCA to MSW treatment and recycling, as well as for energy reuse, has become very useful in the modern world. An important aspect of LCA applied to MSW is the separation and assessment of each phase through generic models, (for example collection, landing, incineration, anaerobic digestion, and composting) which then can be combined to represent a specific MSW management system. Some of these models are purely based on LCA, while others include costs and may be more sophisticated in calculating results.

Comparisons of LCA treatment of MSW can be made between conventional processes and landfill types. LCA can assess the destination landfill, and assess where a mixed composition of waste is treated in a conventional manner by degradation in the soil, or using alternative ways, in which the residue is separated and treated in order to reduce environmental impacts. Separation may be done at the source, and therefore the different fractions must be collected separately. Alternately, depending on the destination, it may be more cost effective to separate fractions after collection. Treatment options can range from recovering a product for reuse, material recycling, or treatment for energy recovery. In recent decades, many researchers and organizations, such as the International Organization of Standardization (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC), have contributed to the development of methodologies used for application in LCA. In this regard, many studies have been done in the world to minimize the environmental impact of the disposal of MSW, and to that end, LCA has been widely used.

Several studies are unanimous in concluding that the LCA methodology is an adequate and appropriate tool to support decision-making for the disposal of MSW and its processes, treatment, and energy recovery. These studies conclude that anaerobic digestion and incineration are feasible in terms of environmental impact and can contribute significantly to political and environmental strategies, as well as providing a sustainable energy resource.

Methodology

The program SimaPro 7.3.3 was used specifically to analyse the life cycle impact (LCI) and life cycle impact assessment (LCIA).

SimaPro 7 is a next-generation software, used widely to develop LCA studies. The scope of the study, including the border and the detailing, was defined based on the routes of MSW disposal. The life cycle for MSW was considered to span from the arrival of waste at the landfill, its screening where applicable, treatment processes and reuse of biomass as a source of electricity, and finally the disposal of residual biomass. The evaluation included: the studied routes; the functions of the proposed processes for study; the functional units; the border routes; resource allocation procedures; selected impact categories and impact assessment and the subsequent interpretation; updated data of the destination routes; established assumptions; limitations of the study; analysis of data quality; and critical review of the study.

The CTR-Caieiras

The LCA takes alternative paths of MSW disposal into consideration to use for comparison, using data from the Landfill Caieiras (CTR-Caieiras), located in the Caieiras municipality in the state of São Paulo.

The CTR-Caieiras stands out as a facility for treatment and disposal of solid urban and industrial waste, however, for this study, we considered only MSW processed at the site. The CTR-Caieiras covers an area of approximately 2,000,000 m2 available for the implementation and operation phase of the landfill. The landfill started its operations in 2002, after receiving its Operating License [12].

The CTR-Caieiras receives an average of 8,600 tonnes of MSW per day, of which the largest share (6,000 t) comes from the city of São Paulo; the rest of the MSW comes from the city of Caieiras and some neighbouring municipalities. The CTR-Caieiras has a volumetric capacity of up to 23,000,000 m3, it consists of 5 stages, and has an estimated useful life of 30 years [12]. Currently, the CTR-Caieiras, phases 1 and 2 are closed, with phase 3 in operation, and phases 4 and 5 currently being implemented.

Process Flowchart and Data Collection

LCA methodology was applied to a case study using CTR-Caieiras data, being identified as a study for the MSW border provisions of landfills. Inventories used within the study took into account inputs and five paths, as follows:

Path 1. From the arrival to the MSW landfill to the burning of biogas at the flare;

Path 2. From the arrival to the MSW landfill to generating electricity from landfill biogas;

Path 3. From the arrival to the MSW landfill to generating electricity from biogas generated through biological mechanical treatment;

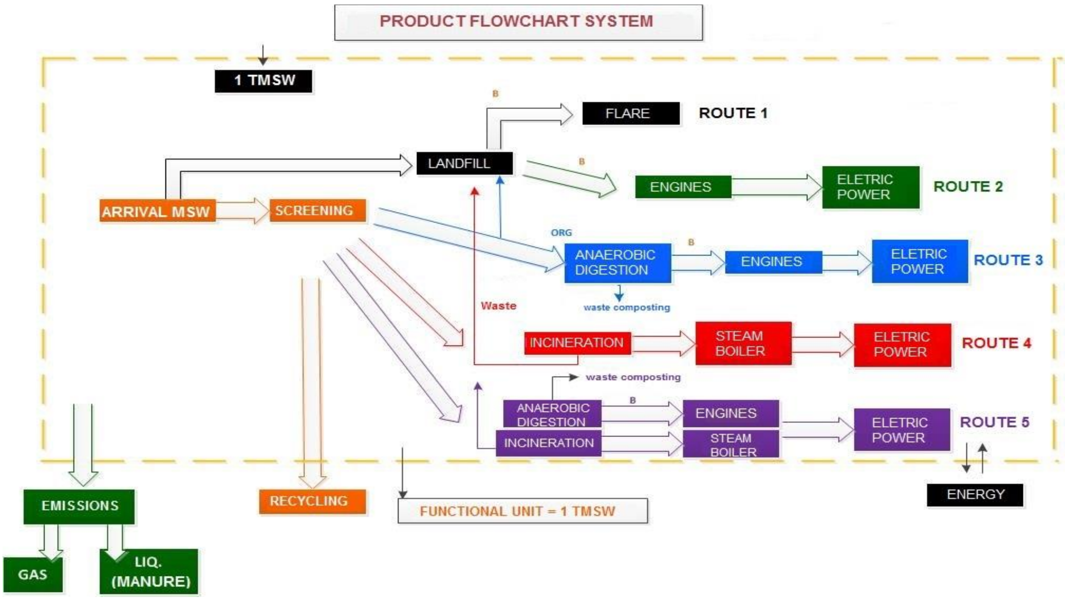
Path 4. From the arrival to the MSW landfill to generating electricity through incineration.

Path 5. From the arrival to the MSW landfill to generating electricity through mechanical biological treatment and incineration.

As a basis for the study, a unit of 1 ton of MSW was delivered to the CTR-Caieiras, and system boundaries were established between the arrival of MSW to the landfill and the delivery of generated power.

Paths and boundaries set for the studies can be seen in Figure 1.

Figure 1. Product system flow.



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Regarding the paths considered for this job, all data on waste characterization, screening, grounding, emissions, gas collection systems, and burning methane at the flare, were from the CTR-Caieiras as mentioned above and therefore the results of environmental impacts reflect only this scenario. For other paths, data would be different and result in different conclusions.

Because of a lack of data in Brazil regarding MSW anaerobic digestion and incineration technology, the data and information used for the analysis were obtained from a leader in the technology and literature, from the city of Boras in Sweden.

With regards to generating electricity through the thermal process (incineration), some data was collected in Boras, since there exist implemented and consolidated operational examples in that city. As for the generation of electricity from biogas, data was obtained from the Bandeirantes Landfill, in São Paulo, where there is technology installed for this type of conversion.

Data collected abroad, and elsewhere, were treated and customized to the CTR-Caieiras scenario so that they could reflect the local reality.

For the studies, Ecoinvent V2.2 inventories were used, which are a part of the software SimaPro 7.3.3. Using these inventories as reference, they were adjusted to the reality of the CTR-Caieiras, making it possible to conduct a comparative analysis of the environmental and human health impacts by TRACI method (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) used by the United States Environmental Protection Agency (EPA) that were created using different scenarios, in view of the relative values of environmental impacts and effects of selected categories listed below:

- Global warming
- Ecotoxicity
- Depletion of Ozone Layer
- Oxidation Photochemistry
- Respiratory Effects
- Carcinogenic and non-carcinogenic substances
- Acidification
- Eutrophication

The MSW inventory is composed as follows:

- 14% paper
- 4 % cardboard
- 21% plastic
- 43% organic
- 4% mineral
- 5% laminated packaging

- 3 %glasses
- 4% tissue
- 2% other materials

Functional unit: 1 ton of MSW disposed in the CTR Caieiras.

Paths 1, 2 and 4 resulted in a 50% moisture content of the MSW. Paths 3 and 5 resulted in a 22.9% moisture content of the MSW.

Traditional pollution categories, including ozone depletion, global warming, human health criteria, smog formation, acidification, and eutrophication have been included within the TRACI.

Here is a description of the different environmental categories.

Acidification

Acidification is the increase in hydrogen concentration (H + ion) in a given environment. This may be the result of the addition of acid (e.g. nitric acid and sulphuric acid) in the environment, or the addition of other substances (e.g. ammonia), which increase the acidity of the environment due to various chemical reactions and/or biological activity, or even by natural circumstances such as soil concentration changes due to changes or increases in local plant species.

Acidifying substances are often found in air emissions, which can be transported over long distances prior to wet deposits (as acid rain, mist, fog, or snow), dry deposits, or as fine particulate matter in soil or water. Sulphur dioxide and nitrogen oxides that come from fossil combustion have been the world’s largest contributors to acid rain [13].

The indicator used to measure the potential acidification is equivalent moles of hydrogen ion (H + mol eq.).

Eutrophication

Eutrophication is the enrichment of an aquatic ecosystem by nutrients (phosphates and nitrates) that accelerate biological productivity (unwanted growth of algae and aquatic vegetation, such as weeds) and thus produce an accumulation of algal biomass [13]. Although nitrogen and phosphorus have an important role in land fertilization for agriculture and the propagation of other vegetation, excessive discharges of these substances can cause undesirable effects on water systems in their soil beds and their final destination. The indicator used to measure the potential of eutrophication is equivalent kg of nitrogen (N kg eq.).

Global warming

Global warming is the increase in the average temperature in the troposphere, the atmosphere nearest to the earth’s surface. The increase in temperature contributes to changes in climate characteristics. The indicator used to quantify the global warming potential is kg of carbon dioxide equivalent (kg CO2 eq.).

Ozone depletion

Ozone in the stratosphere provides protection from sun radiation, but when depleted, it can lead to increased frequency of human skin cancer and cataracts. Furthermore, ozone depletion has been documented to have an adverse effect on vegetation, animals, marine life, and buildings. The indicator used to measure ozone depletion potential is kg equivalent CFC-11 (CFC-11 kg eq.).

Human health - respiratory effects

Although this category is for all pollutants that impact human health, here is a subcategory of respiratory pollutants, i.e. particulate matter and particulate precursors. Particulate matter is a collection of small particles in an atmospheric environment that is capable of causing adverse effects on human health, including respiratory disease and death. The indicator used to quantify the potential of particulate matter with respiratory effect is kg of particulate matter 2.5 equivalent (kg PM2.5 eq.).

Human health - carcinogenic and non-carcinogenic toxicity and ecotoxicity

During the development of TRACI, human health was represented by three impact categories based on the structure of EPA regulations and behaviour of physical and chemical pollutants of concern. They are: carcinogenic toxicity, non-carcinogenic toxicity, and ecotoxicity.
The indicators used to quantify the potential carcinogenic toxicity, non-carcinogenic toxicity, and ecotoxicity are:

- carcinogenic toxicity - equivalent kg of benzene (benzene kg eq.);
- non-carcinogenic toxicity - kg equivalent toluene (kg toluene eq.); and
- ecotoxicity - kg equivalent dichlorophenoxyacetic acid (2,4-D kg eq.).

Photochemical Smog

Ozone in the lower levels of the atmosphere is created by various chemical reactions, which occur between nitrogen oxides (NOx) and volatile organic compounds (VOCs) reacting in sunlight. The effects on human health can result in a variety of respiratory problems including symptoms of bronchitis, asthma, and emphysema. The indicator used to measure the potential for photochemical smog formation is equal to g x (g NOx eq.).

Results and discussion

Comparative analysis of the environmental profile of the different paths

Results were classified in terms of potential long-term impacts, i.e., considering the potential environmental impacts over a period of 100 years.

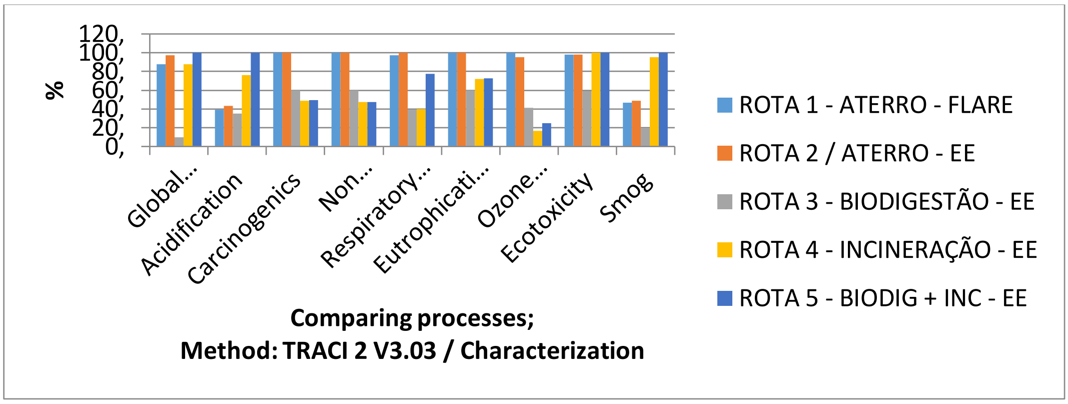
When considering long-term impacts, the greatest areas of concern were regarding carcinogenic substances, non-carcinogenic substances, ecotoxicity, and eutrophication, which were represented by considerable values, as can be seen in the figures below.

Table 3. Impact categories/ long-term, Paths 1 to 5.

Impact category - long tem	**Unit**	**Route 1**	**Route 2**	**Route 3**	**Route 4**	**Route 5**
Global Warming	kg CO2 eq	465.73	514.02	52.70	464.31	529.00
Acidification	H+ moles eq	11.63	12.78	10.30	22.48	29.60
Carcinogenics	kg benzen eq	175.94	175.91	106.00	86.12	86.50
Non Carcinogenics	kg toluen eq	5.71E+06	5.71E+06	3.43E+06	2.69E+06	2.72E+06
Respiratory Effects - PM	kg PM2.5 eq	0.04	0.04	0.02	0.02	0.03
Eutrophication	kg N eq	6.78	6.78	4.07	4.90	4.93
Ozone Depletion	kg CFC-11 eq	5.95E-06	5.67E-06	2.47E-06	9.93E-07	1.52E-06
Ecotoxicity	kg 2,4-D eq	3.94E+04	3.94E+04	2.37E+04	4.02E+04	4.05E+04
Smog	g NOx eq	0.25	0.26	0.10	0.50	0.53

Source: developed by author

Chart 1. Routes comparison, long-term.



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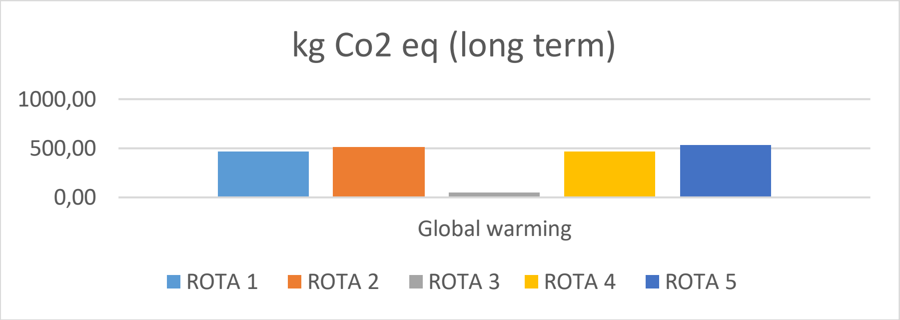
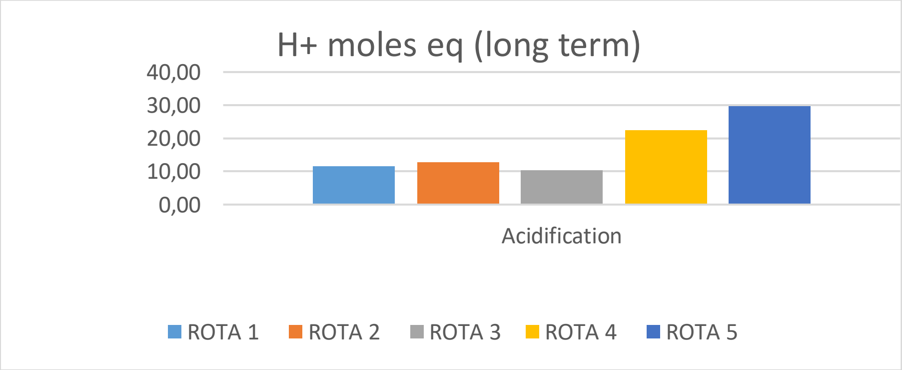
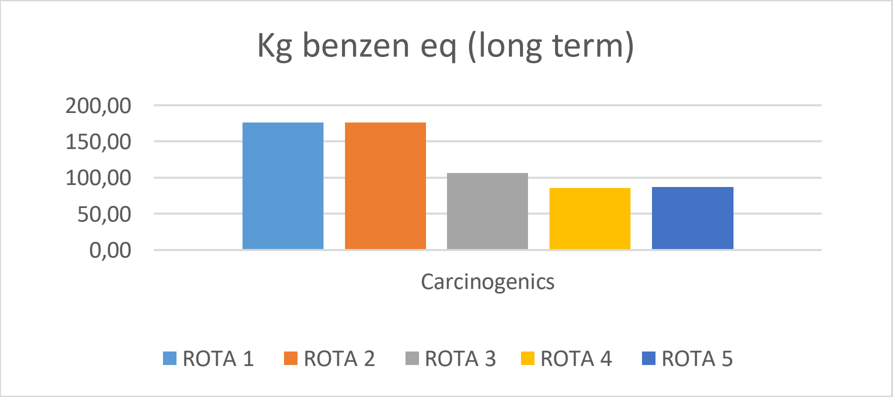
Charts 2-4. Global warming, acidification, carcinogens, long-term impacts, Paths 1-5.







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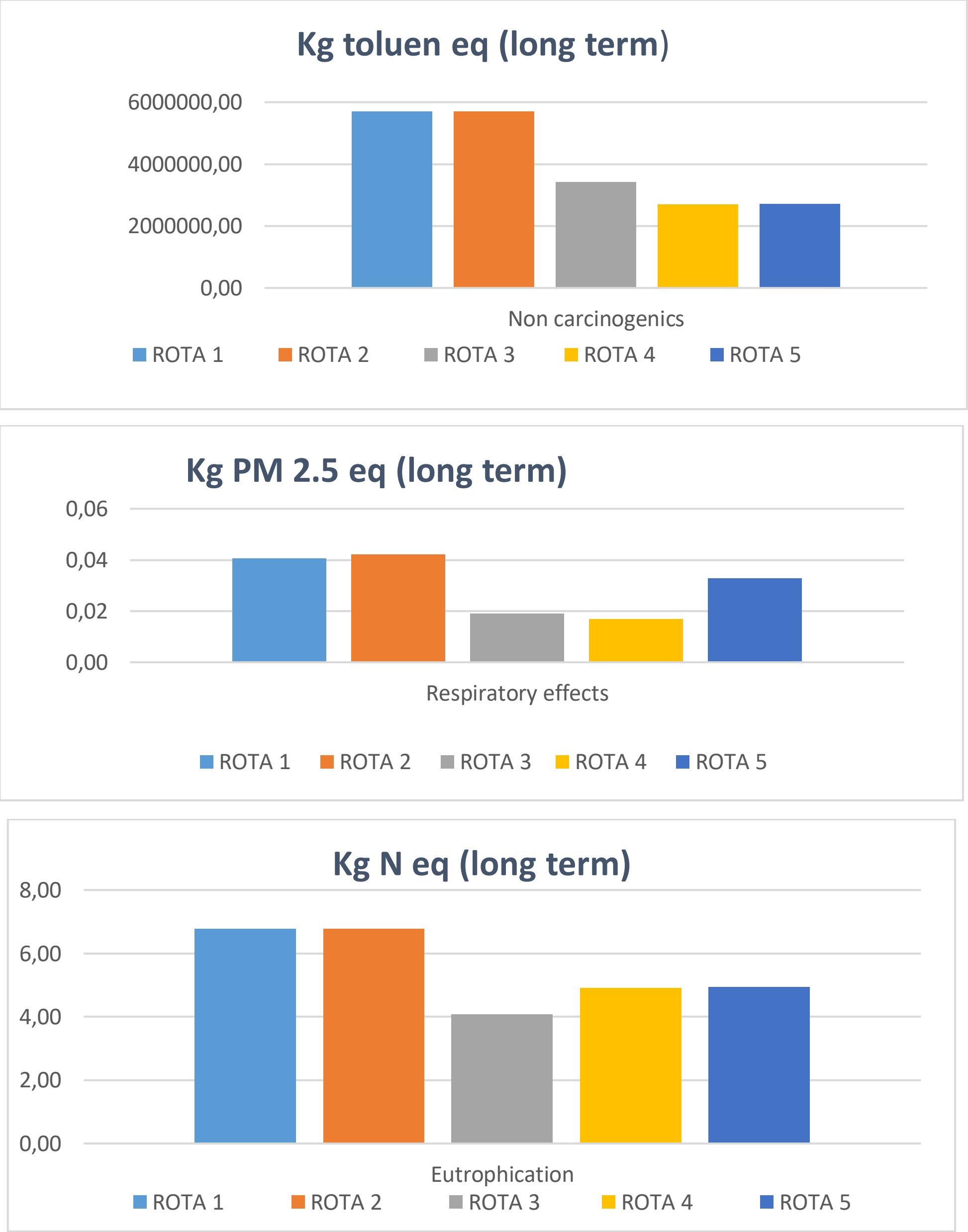
Charts 5-7. Non-carcinogens, respiratory effects, eutrophication, long-term impacts, Paths 1-5.



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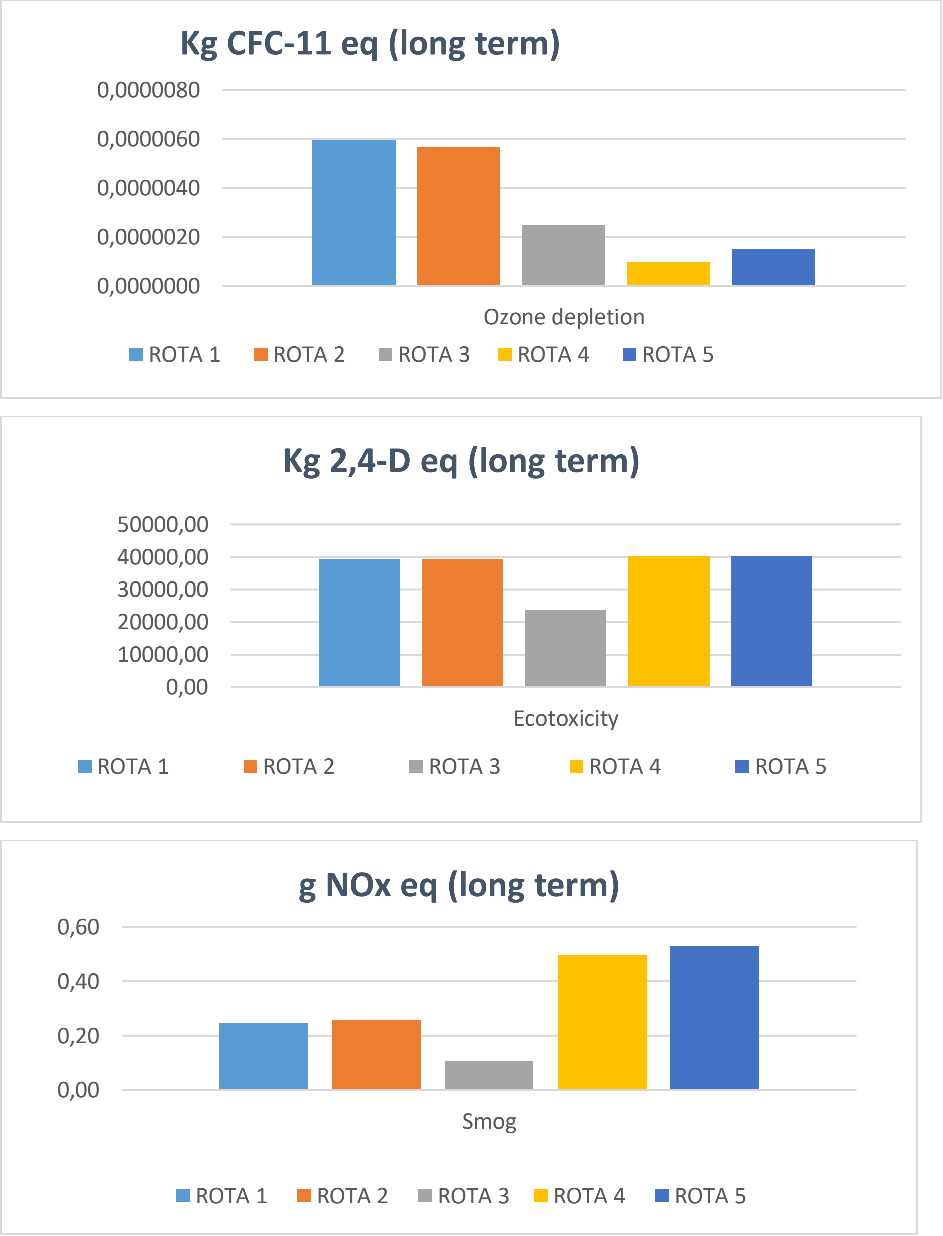
Charts 8-10. Ozone, ecotoxicity, smog, long-term impacts, Paths 1-5.



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In the case of impacts caused by carcinogenic substances, related to the landfills, Paths 1 and 2 present the greatest risk. Potential impacts from non-carcinogenic substances and ecotoxicity are also of an elevated risk for the first two paths, which leaves Path 3 as having the least negative impact.

The results show that Path 3, related to the biological mechanical treatment process is presented as being the least harmful with respect to the potential impact of global warming and acidification.

The results also indicate that leaving MSW in the landfills has a strong negative impact in most categories, except for acidification and photochemical smog in which paths that include incineration cause greater impact.

In the case of eutrophication, Routes 4 and 5 have significant long-term aggression.

In the case of the potential impact of ozone depletion, landfills without incineration appear to be the most deleterious in the long-term.

Regarding smog, the incineration paths contribute the most to a negative outcome over the long term.

It can be observed in Paths 1 and 2, that the differences are not substantial, and due to the characteristics of the processes, analysis shows them to be very similar; in fact, the only real difference between Paths 1 and 2 is in the electricity generation process. While Path 1 considers how biogas flaring affects the values, Path 2 considers how electricity generation makes an impact. However, in both paths, the overall use of the landfill process is similar, and therefore the overall impacts, when compared, exhibit very similar values.

Results for Paths 1 and 2 also show they pose the greatest danger in terms of ecotoxicity, human health, and carcinogenic and non-carcinogenic toxicity, as a result of MSW leachate contaminating the soil and groundwater. Regarding other analysed categories, the risks are low for both paths.

Path 3 also shows an elevated risk regarding ecotoxicity, human health, and carcinogenic and non-carcinogenic toxicity, but at a lower intensity than Paths 1 and 2. This is mainly due to removal of organic waste in this path, which is diverted towards anaerobic digestion process, thereby reducing leachate from the landfill. Path 3 also poses the least amount of risk compared to Paths 1 and 2 regarding other potential environmental impacts. The analysis shows that Path 3, when compared to Paths 1 and 2, has the lowest risk of environmental impact.

Looking at Path 4, incineration, conducting mass burning, carries a higher risk than Path 3 regarding environmental impacts and also in ecotoxicity, mainly due to emissions from the combustion process. However, Path 4 presents lower risk values than Path 3 regarding human health and carcinogenic and non-carcinogenic toxicity. This indicates that Path 4 is a better choice than Paths 1, 2 and 3 in the long term.

While Path 5 is similar to Path 3, it differs as it includes an additional step of generating electricity through incineration. Emissions due to the combustion process increases the risk impact of Path 5, compared to Path 3 in regard to ecotoxicity, human health, and carcinogenic and non-carcinogenic toxicity.

Path 5, however similar to Path 4, presents slightly better than the comparative indicators of Path 4, and overall better than Paths 1, 2, and 3. Path 5 is indeed most attractive, considering the results of environmental impacts when weighed against the efficiency of MSW disposal, and the better utilization of WTE.

Comparatively overall, Path 5 presents the best result among the categories of environmental impact considered in this study.

Standardization points to the significance of environmental impacts caused by carcinogenic and non-carcinogenic substances and substances that contribute to ecotoxicity. While impacts related to global warming, photochemical smog, ozone depletion, and acidification, pose less risk than the aforementioned categories, they should still be considered in individual analysis for each path. For example, in those paths that include combustion processes, atmospheric emissions and related impacts should be considered. Note also that the environmental impacts of Paths 1 and 2, which examine total landfill, show the greatest risk of impacts to the environment.

Although there is still much concern about emissions from combustion processes used in the incineration of MSW, modern technologies have evolved substantially and today are quite reliable in their capability to separate and contain hazardous pollutants, explaining why these are commonly used in developed countries that have strict emissions guidelines. That is why these technologies were considered in the compilation of the lists used in this study, verifying that the environmental impacts caused by them, compared to other technologies, may be considered to be less harmful to the environment.

Conclusion

Proper management of MSW can provide an additional energy resource, helping to reduce a municipality's consumption of fossil fuels and minimize its environmental impacts. Thus, this study's main objective was to study alternatives of MSW disposal and energy recovery by identifying environmental impacts and comparing these alternatives, and propose guidelines for evaluating the environmental aspects.

The study results showed when comparing five different path options, the generation of electricity from the combined processes of mechanical biological treatment and incineration is the most attractive in terms of environmental impacts (considering standardized results). Prior to current technologies, incineration was not considered a safe option due to the negative environmental impacts of its byproducts; however, with technological advancements in recent decades, incineration has become much more reliable in the removal of toxic emissions. Incineration is now even able to conform to the strictest environmental laws in the world, and in Brazil.

In terms of environmental impacts (excluding human health impacts), options which consider electricity generation from biogas are most attractive (considering standardized results) in the long-term when compared to incineration, although with regard to some environmental categories, incineration proves to be more attractive, even when comparing the impacts in the short-term.

Other important factors that can be considered as bottlenecking the development of WTE projects are the lack of incentives in sector policies.

As a general conclusion, this study identified the existence of options and opportunities for the implementation of projects related to electricity generation in Brazil using MSW, especially through the combined process of biological mechanical treatment and incineration, with the exception that there are still socio-political-economic barriers that need to be overcome. However, the technologies presented here should be further studied, and implemented where appropriate, as they offer an efficient and sustainable means by which to treat and recover energy from MSW, with this claim supported by the fact that these alternatives are being use in developed countries throughout the world.

Highlighted below are some recommendations to encourage the viability of investments in this area:

- improvements in the environmental licensing system, as this is still very complex and time-consuming in Brazil;
- implementation of bills to adopt tax incentives to carry out WTE projects;
- expand the dissemination of studies on electricity generation technologies from MSW; and
- amalgamate municipality waste collection in order to achieve scale to facilitate implementing projects that convert energy from MSW.

Further studies are needed to assess projects currently underway, which will help to further inform the data and provide more robust results with respect to inventory related to processes of landfilling and waste treatment operations. Due to the lack of local inventories, it is still necessary to use inventories abroad and adjust the data to fit the local reality, which makes the study process that much more complex and limited. However, compiling more data will allow more accurate estimates to be used for the dissemination of technological information to support investments in electricity generation from MSW, allowing decision-makers to implement the most efficient management strategies and contribute to a more diversified national energy matrix.

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