Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in São Paulo City

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Abstract

There is increasing concern about landfilling of biodegradable wastes. Therefore, biological treatment processes such as composting and biogasification have been considered as alternative strategies for managing those wastes. In this work, life cycle assessment was employed to compare the environmental impacts of landfilling, composting, and biological treatment of municipal solid waste in São Paulo City, Brazil. Energy consumption, recovered resources, and emissions to air and water were quantified and analyzed in terms of their potential contribution to global warming, acidification, and nutrient enrichment impact. The results demonstrated that processes that require high levels of energy consumption, such as wastewater treatment, play an important role in the outcome of environmental impact potentials. It was found that the landfilling of all waste is generally the worst strategy from an environmental point of view. However, significant reductions in the resulting impacts can be accomplished through biogasification and composting of the biodegradable fraction. Regarding composting, the application of a biofilter for gas treatment reduced significantly the gaseous emissions.

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1. Introduction

Currently, around 95 wt.% of the municipal solid waste (MSW) collected in São Paulo City, Brazil, is disposed in sanitary landfills and 70 wt.% of this waste is biodegradable. Although modern landfills are constructed to protect the environment, three major disadvantages for such strategy can be pointed out: high emission of methane, a potent greenhouse gas; risk of leachate leakage and consequent contamination of water streams; and lack of landfill sites. In São Paulo City, the development of areas covered by tropical forest is necessary for obtaining new landfill sites. Therefore, it would be of interest to study different strategies of waste treatment to decrease the burden on the environment. Two other options are considered in this study: composting and biogasification (anaerobic digestion).

Environmental life cycle assessment (LCA), a system analysis tool that has been recently applied to MSW management (Barton et al., 1996; Weitz et al., 1999; White et al., 1999), was chosen for evaluation to ascertain if environmental benefits could be obtained through a change in the MSW treatment system. In this paper, the results of an LCA for comparing composting, biogasification, and landfilling are presented, and possible improvements are discussed. A life cycle inventory (LCI) model based on world average data was constructed and adapted to the Brazilian conditions (waste composition and electricity source); and the results were connected to a life cycle impact analysis (LCIA) model. Therefore, resource consumption, emissions, and environmental impacts were assessed.

2. Methodology

The life cycle assessment was performed for five scenarios of waste management: landfilling, landfilling with energy recovery, composting, composting
followed by gas treatment (compost with biofilter), and biogasification.

A comparison among the scenarios was done by assessing the treatment and disposal of 1 ton of MSW. The reference composition of the waste is from the results of an analysis of residential waste in São Paulo City (Orth and Motta, 1998), as shown in Table 1.

2.1. System boundaries

In an LCA, the choice of system boundaries and assumptions is crucial for the results and their interpretation. In this study, an integrated waste management plan was taken into account; therefore, the disposal of both biodegradable and non-biodegradable wastes was included within the system boundaries. Fig. 1 presents the system boundaries of this study; since different waste treatment methods may fulfill different functions, the approach of expanded system boundaries was adopted (Finnveden, 1999). The core system involves the treatment of the waste and the expanded system includes the compensatory processes to make the different types of treatment comparable. For a better understanding of the source of environmental impacts, the scenarios were divided into stages, as shown in Fig. 2. The composting (COM), the composting with biofilter (CBF), and the biogasification (BIO) scenarios included the main treatment (MT), wastewater treatment (WT), final landfill disposal (LD), and leachate treatment (LT). The landfill (LAN) and the landfill with energy recovery (LER) scenarios were composed of the landfill itself and the leachate treatment plant. Reduction of impacts from producing electricity was addressed in the energy recovery (ER) stage, while reduction from substitution of fertilizer by compost was addressed in the materials recovery (MR) stage. These two last stages are not shown in Fig. 2, but are represented in the expanded boundaries of Fig. 1.

Even though wood can be biologically degraded in a landfill, it usually cannot be degraded in an anaerobic digester due to its slow degradation rate. Therefore, wood waste was landfilled in all scenarios.

Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Kitchen garbage</th>
<th>Paper, cardboard</th>
<th>Wood</th>
<th>Textiles</th>
<th>Plastic</th>
<th>Rubber, leather</th>
<th>Glass</th>
<th>Metal</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>49.5</td>
<td>18.8</td>
<td>1.3</td>
<td>2.4</td>
<td>22.9</td>
<td>0.6</td>
<td>1.5</td>
<td>2.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 1. System boundaries for this study.
Emissions from the construction of facilities were not included in this study, because it is considered that these emissions are small compared to those released during the operational stage of the facility. If composting and biogasification reactors were installed at the same site as the landfill, the collection and transportation could be assumed to be identical in all scenarios; therefore these stages before the waste treatment were omitted.

2.2. Scenarios description

Within the landfill, a gas collection system with 50% gas removal was assumed. In other words, 50% of methane gas is released to the atmosphere. While in the LAN scenario the collected gas is flared; in the LER, the gas is cleaned and burned in a gas engine with 30% energy recovery efficiency. In both scenarios, a leachate treatment plant was assumed. Methane emissions were calculated based on IPCC Guidelines Methodology (IPCC, 1997, 2000). Carbon dioxide emitted in the landfill was not accounted as contributor to the GWP, because it is not from anthropogenic origin. Other gaseous emissions were described by White et al. (1999), while the leachate treatment plant (LTP) was described by Tsurumaki (1998). Solid emissions from LTP are treated and landfilled.

In both COM and CBF scenarios, it was assumed that 50% of the waste is converted to compost, and the other 50% is lost due to respiration and evaporation (White et al., 1999) as ammonia, nitrogen gas, and nitrous oxide (Dalemo et al., 1997). The compost was assumed to replace chemical fertilizer (urea) in the composting scenarios. Cleaning of gaseous emissions from the composting process was assessed in the CBF scenario; in which a gas cleaning system, consisting of a condensation step with recycling of condensed liquid to the compost followed by a biofilter, was assumed to decrease 90% of the ammonia and nitrous oxide emissions (Dalemo et al., 1997). There are no wastewater emissions from the composting plant in this study.

In the BIO scenario, it was assumed that 30% of the energy from the biogas can be recovered and converted into electricity. From the electricity generated, 30% is applied within the plant to operate the process (White et al., 1999). Wastewater emissions are treated in a wastewater treatment plant (WWTP), which consumes 86 kWh electricity per kg of COD removal (based on Tsurumaki, 1998). In the wastewater treatment plant, 90% of COD and Total-N compounds are removed. Solid emissions from both the biogasification plant and WWTP are treated and landfilled. The energy and chemicals consumption for the WWTP and LTP were also accounted.

2.3. Life cycle inventory

Energy consumption, resources input and recovery (electricity, compost), and pollutant emissions to the atmosphere (CO₂, CH₄, SO₂, NO₂, N₂O, H₂S, HCl, HF, NH₃), and water (COD, Total-N, Total-P) were estimated for all scenarios. The emissions generated during production of auxiliary materials, fuels, and electricity

Fig. 2. Flowchart of scenarios.
were included. Emissions from producing urea were used for accounting for the avoided emissions of replacing chemical fertilizer by compost. The sources of data were as follows: NIMS (2000) was the source of data for urea production; and JEMAI (2000) was used for accounting emissions of diesel combustion for spreading waste in the landfill. Since no life cycle inventory data for Brazilian electricity was available, it was determined by applying the emission factors for electricity generation presented in SAEFL (1998) in the following proportions: hydropower (94%), oil (3%), coal (2%), and nuclear (1%) power plant (based on MME, 2000).

2.4. Life cycle impact analysis

The emissions accounted in the inventory stage were arranged into three environmental impact categories: global warming potential (GWP), acidification potential (AP), and nutrient enrichment potential (NE). Within each impact category, each emission was multiplied by an equivalency factor to obtain an impact potential value. It is important to note that the calculated impact corresponds to a potential impact that could occur, and not to an actual one. The actual occurrence of an impact will depend on many factors, mainly related to the site characteristics. The impact categories, their respective emissions, and equivalency impact factors applied in this study are presented in Table 2. The scientific background for obtaining these equivalency factors is explained in Hauschild and Wenzel (1998).

3. Results

The life cycle inventories of the scenarios were calculated. The energy and auxiliary product consumptions and emissions of each scenario were associated to the impact categories addressed. Results of the LCIA are presented and discussed below.

In Figs. 3–5, the obtained impact potentials for the studied scenarios, including both final values and contributions as percentage of stage, are shown. The stages are expressed as follows: main treatment (MT), which corresponds to biogasification, composting, or landfilling processes; final landfill disposal (LD); wastewater treatment (WT); and leachate treatment (LT). The avoidance of environmental effects by energy or materials recovery (ER or MR) is expressed as a negative value.

Fig. 3 presents the global warming potential (as kilogram of CO$_2$/ton of waste) for the different scenarios assessed (left) and the contribution of each stage (right).

The landfilling of all fractions of waste (current situation) presents the highest GWP, even if the landfill gas is used for producing electricity (LER scenario). When the biodegradable fraction is supplied to composting or biogasification, a very significant reduction of GWP can be attained.

Regarding the contribution of the different stages, the GWP in the landfilling scenarios is mainly due to the methane generated by the biological degradation. Since the composting and biogasification processes have low energy consumption as well as very low greenhouse gas emissions, COM, CBF and BIO have low GWP. Therefore, the contribution of other stages such as the final landfill disposal became significant. Disposal of wood wastes was assumed to be in a landfill, then generating methane; even though the volume of methane is small, its contribution is rather large because the greenhouse emissions of other stages are very small.

In the case of the BIO scenario, the wastewater treatment also has a significant impact. This is because both LTP and WWTP have a high energy and chemicals consumption. However, only the WT stage has a significant contribution to the impact potential in this scenario because the load in the leachate is low since the biodegradable fraction is not landfilled.

The recovery of energy and materials has a limited contribution to the reduction of GWP because most of the electricity production in Brazil that could be replaced by the generated electricity comes from hydropower plants that have a low greenhouse gas emission.

Fig. 4 shows the acidification potential (as kilogram of SO$_2$/ton of waste) for all scenarios (left) and the contribution by stages (right).

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Table 2

Impact categories, substances, and equivalency factors (Hauschild and Wenzel, 1998)

<table>
<thead>
<tr>
<th>Global warming (GWP) as kg CO$_2$</th>
<th>Acidification (AP) as kg SO$_2$</th>
<th>Nutrient enrichment (NE) as kg NO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions</td>
<td>Factor</td>
<td>Emissions</td>
</tr>
<tr>
<td>(a) CO$_2$</td>
<td>1</td>
<td>(a) SO$_2$</td>
</tr>
<tr>
<td>(a) CH$_4$</td>
<td>25</td>
<td>(a) NO$_2$</td>
</tr>
<tr>
<td>(a) N$_2$O</td>
<td>320</td>
<td>(a) H$_2$S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a) HF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a) HCl</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a) NH$_3$</td>
</tr>
</tbody>
</table>

"(a)" indicates emissions to the atmosphere; "(w)" indicates emissions to the water.

* Time horizon of 100 years was adopted for GWP.
Regarding acidification potential, the COM scenario presents the highest impact potential due to a high emission of gaseous ammonia. The installation of a gas cleaning system, as represented in the CBF scenario, reduces it significantly; ultimately this scenario presents a smaller impact than both LAN and LER.

The BIO scenario presents the lowest acidification impact potential, since there are no emissions of acid gases in the main treatment. Therefore, the acidification potential in this scenario is due to the energy consumption for wastewater treatment.

Fig. 5 shows the nutrient enrichment potential (as kilogram of NO₃⁻/ton of waste) for each scenario. Even though biogasification is responsible for high N-compound emissions, it still presents much smaller nutrient enrichment impact than landfilling. LAN, LER and COM scenarios have similar impacts, however, the composting impact was slightly lower due to the fertilizer substitution (materials recovery). Regarding composting, nutrient enrichment potential is due to the emission of ammonia to the air. Therefore, the application of a gas treatment system with ammonia removal reduces this impact potential significantly, thus the CBF scenario presented the lowest NE impact potential, with a negative value. This means that the substitution of urea by compost, which avoids N-compound emissions during urea production, is more significant than the emissions that would occur in producing compost.

In both biogasification and landfilling, the high N-compound emissions to the water are associated with the NE impact. In this scenario, the NE is mainly due to the treatment of the biodegradable fraction, i.e., the main treatment itself.
4. Discussion

When all waste is landfilled, the biodegradable fraction produces methane. Due to the intrinsic conditions of the landfill, not all landfill gas can be collected. Usually no more than 50% of the gas is flared or recovered in a landfill. Therefore, a significant amount of landfill gas is lost to the environment contributing to both global warming and acidification potentials. The biodegradable fraction also releases substantial amount of organic compounds (as COD) and nitrogenous compounds (as Total-N) to the leachate. Additionally, the conditions in a landfill are such that not all leachate can be collected because the landfill liner can fail and part of leachate is lost to the environment (White et al., 1999; Rieradeval et al., 1997). Moreover, the leachate treatment itself contributes to increase the environmental impact due to a high energy and chemicals consumption. Even if electricity is produced, landfilling is still the strategy with the highest environmental impacts, except for acidification potential in COM scenario without gas cleaning.

When biodegradable wastes are diverted for composting or biogasification and only other wastes are landfilled, a significant reduction in environmental impacts is observed.

In the biogasification process, the fermentable wastes produce biogas in controlled conditions; therefore all the biogas can be used for producing electricity. On the other hand, a large volume of wastewater is generated and the energy used for its treatment results in significant impacts. However, even with high wastewater emissions the BIO scenario has still smaller impacts than the LAN and LER scenarios. As it can be observed in Figs. 3 and 4, in the BIO scenario the final landfill disposal has a more substantial contribution to the GWP and AP than the biogasification (main treatment) itself.

In the case of composting, it has opposite characteristics of biogasification in terms of environmental releases. It is a dry process, so water emissions are low. On the other hand, the gaseous emissions are significant. To decrease gaseous emissions, a biofilter can be installed, as investigated in the CBF scenario. In this case, 90% of ammonia and nitrous oxide emissions are recovered, so the acidification and nutrient enrichment potentials decrease significantly. The removal of nitrous oxide also contributes to a GWP reduction. Similarly, with the BIO scenario, the final landfill disposal stage of COM scenario is a significant contributor to the GWP. The production of compost can decrease the environmental impacts due to the avoided emissions by substituting a chemical fertilizer, such as urea.

The impact of the BIO scenario may be overestimated, because high water emissions were assumed compared to much lower emissions assumed in some studies. In that case, biogasification would be judged more environmentally sound.

For all environmental impact categories assessed, the impact reduction due to the generation of electricity in Brazil was not very high because electricity is mainly from hydropower origin. Despite the small reduction in the environmental impacts, electricity production is a suitable strategy due to the lack of electricity in São Paulo area during the dry season. Moreover, the Brazilian electricity generating profile may change due to an increasing use of thermal power generation.

Regarding fertilizer substitution by compost, due to the relatively low nitrogen concentration, large amount of compost is necessary to substitute a rather small amount of chemical fertilizer. Even so, fertilizer substitution has decreased acidification and nutrient enrichment potentials. Application of compost to the soil is a valuable option because it can act as both fertilizer and soil conditioner.

5. Conclusions

The comparison of the environmental impacts of landfiling, composting, and biogasification of municipal solid waste in São Paulo City were presented and discussed here. Landfilling was the scenario with the highest environmental impacts, except in the case of acidification potential, in which composting presented the highest potential. However, the high potential impact from the composting process can be reduced by adding a gas treatment to the system. Even with electricity generation from the landfill gas (LER scenario), landfilling is still an option with high environmental impacts.

There is a trade-off among BIO and CBF scenarios; while the BIO scenario presented the lowest acidification potential, CBF presented the lowest nutrient enrichment potential. However, the potential environmental impacts were not overly different between them. The composting without gas treatment presented higher environmental impacts than biogasification. Finally, both composting and biogasification can decrease significantly the environmental impacts compared to landfilling the waste.

The results obtained are applicable to the conditions in São Paulo, since waste composition and electricity inventory data are specific to this city. Both waste composition and carbon-intensity of energy sources are very important factors to the outcome of the environmental impact of an MSW management system. In countries using high carbon-intensity energy sources for electricity, results may be different. This shows the importance of assessing local conditions in the evaluation of the environmental impact of options for waste management. Such site-specific analysis would assist in conducting an appropriate decision-making process.
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References