Modelling of a sanitary landfill for developing countries to improve the reliability of Life Cycle Assessment studies

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Abstract. In developing countries, such as Brazil, the main destination of municipal solid waste is sanitary landfills. In Life Cycle Assessment (LCA) studies, the entire life cycle of the product or process is considered, therefore it is necessary to take into account the destination of the waste and by-products of the process in question. For a reliable and representative LCA study, these destinations have to be illustrative of the place where the study is conducted in. Regarding the treatment and disposal of organic solid waste, the main LCA databases, such as Ecoinvent 3.0, consider sanitary landfills modelled in European standards, which include processes that are not common in developing countries. In light of this reality, the aim of this study was to model a sanitary landfill that corresponds to the case of the said countries and provide a methodology to improve the significance of environmental studies, which can also be used with primary data. The model used literature data based on Brazilian reality, considering the operation of the landfill (transport and emissions and diesel usage in the spreading of the waste); biogas generation and treatment; leachate generation and treatment using stabilization lagoons and its emissions. When compared to landfill based on European reality, differences up to 80% can be observed in some potential environmental impacts.

1 Introduction

In Brazil, solid waste management is defined according to National Solid Waste Policy, instituted in 2010, which establishes principles, goals and responsibilities in this topic [1]. Among its main points, there is the elimination of open dumps, which is an inadequate waste destination, where there’s no control over the type of waste deposited or the generation of byproducts. The utilization of open dumps as a final destination for solid waste leads to high damage to the environment and the surrounding communities.

These irregular dumps were the final destination of 68% of the municipal solid waste (MSW) in 2000 and 49% in 2008 [2]. The law that created the Policy determined that from 2014 the use of open dumps would be prohibited, but the waste from 1,560 municipalities, which represents 28% of the total number, still had the dumps as final destination [3]. Although this movement promoted more
sustainable processes such as recycling, it still has low representation in the national waste destination scenario, given that only 32% of all produced recyclables were retrieved in 2017 [3].

Faced with this situation, the reduction in the number of dumps was followed by the increasing in sanitary landfills participation as final destination of the MSW, going from 17% in 2000, to 29% in 2008 and 40% in 2017 [2, 3]. Landfills are a common destination in developing economies and they seek the minimization of environmental impacts through soil waterproofing, construction of drainage and collection systems for biogas and leachate while it also has to have a joint closure plan and use for the area after its service life. These landfills aren’t, however, designed to receive only inert waste, but also MSW, which in Brazil has the approximate content of 51% organic matter [2]. The degradation of these residues with high percentage of organic matter in the landfill leads to the production of by-products such as leachate and, above all, biogas, which can be harnessed energetically, although it is still incipient in the country [1].

As a way of comparing possible waste management strategies, there’s the Life Cycle Assessment (LCA). This methodology is used for quantification of environmental impacts related to a product of service through the inventory of its used resources, waste generated and emissions in the complete life cycle of the product. The LCA allows the identification of hotspots, scenarios tests and comparison of alternatives, consisting of an important environmental management tool. An critical step of the LCA is the Life Cycle Inventory (LCI), where the inputs and outputs of the analyzed process are identified and quantified. Subsequently, the data present in the LCI will be converted into impact potentials. Therefore, special attention is needed at this stage because it will be determinant for the results and consequently for the conclusions of the study.

In order to consider the complete life cycle of the product or service, it is also necessary to consider the destination of the waste generated, and for this study to be representative, it should be illustrative of the place where the study is conducted. However, the application of LCA to evaluate the environmental performance of solid waste management systems is still elementary in developing countries [4, 5]. Given that the systems presented in studies from developed countries may not be suitable for developing countries [5], mainly because of differences in waste characteristics and because they include steps and processes that are not part of their realities, there is a clear need for more studies on the management of solid waste in the developing world. Currently, the work in this subject is concentrated in Asian countries [6].

The literature review conducted by Ibáñez-Forés et al. (2018) identified researches involving solid waste management in Brazil and showed that the vast majority of them didn’t national data. Among the studies cited, Mendes et al. (2004) and Ibáñez-Forés et al. (2018) inventoried sanitary landfills using European data [7, 8]; The work of Reichert et al. (2014) also compared waste destinations and the modeled landfill was from a large municipality, where there is energy generation and commercialization from the biogas produced, which would not be applicable to small municipalities [9]; and the work of Leme et al. (2004) focused only on the generation and use of landfill biogas, using data from the Intergovernmental Panel on Climate Change [10].

The sanitary landfills available in LCA softwares are not compatible with Brazilian reality either, since processes modeled by the European Life Cycle Database (ELCD) and Ecoinvent 3 follow European standards. In the first one, for example, the considered treatment of leachate is through the use of activated carbon and flocculation techniques, and the second one considers the incineration of the sludge generated in the leachate treatment. None of these methods are representative in the Brazilian scenario and the use of these processes in a LCA study would not lead to a verifiable result.

Given the large number of Brazilian municipalities, 5,570, the number of sanitary landfills, 2,239 [2] and the growing trend of this number given the current national policy, it becomes increasingly necessary to access a landfill model for the implementation of other LCA studies, in order to produce results that are more representative of the country's reality.

Therefore, the goal of this work is the establishment of an emission quantification methodology to be reported in LCA softwares. Based on the characteristics of landfills located in small Brazilian municipalities and the commonly adopted waste management technologies, a life cycle inventory of a
sanitary landfill was constructed, capable of better matching the reality of Brazil and other developing countries, to improve the relevance of LCA studies. The modeled process includes the operation of the landfill (transportation, fuel consumption in the disposal and compaction of the waste), degradation of the solid waste, generation and treatment of biogas and leachate. The implantation and decommissioning of the landfill were not considered.

2 Materials and methods

2.1 The LCA methodology
LCA is used to assess potential environmental impacts related to a product or process through the inventory of its resources, wastes and emissions. As a management tool, LCA makes it possible to compare the technical aspects and environmental performances of alternative scenarios, and to identify hotspots as well as opportunities for improvement in the life cycle under study.

As described in ISO 14040 (2006), an LCA study is organized in four stages \[11\]. The goal and scope definition stage addresses the purpose and scope of the study by establishing the system boundaries. The following items should be described: the goal of the study, the processes included and what basis is to be used, for example, the functional unit. The second stage is the life cycle inventory (LCI), which consists in the identification and quantification of the inputs and outputs of each unit process that takes place within the established system boundaries. In the impact assessment stage, the inventory is converted into environmental indicators for the impact categories that will vary depending on the method used. The final stage includes analysis of the results and assessment of conclusions based on the points mentioned in the definition of the goal and scope.

The present work focuses on presenting the LCI of a sanitary landfill that can be applied to small municipalities in countries under development so they can be used in LCA studies to improve its reliability.

2.2 Methodology for the construction of the Life Cycle Inventory of the sanitary landfill
In this stage, the sanitary landfill was inventoried with the methodology first developed in Gutierrez (2014) \[12\]. Since Brazil is a country of continental dimensions generalizations were made necessary based on nation-wide data to guarantee its significance. The landfill is equipped with systems to capture and treat the biogas (flairing) and leachate (in a system composed by an anaerobic lagoon followed by a facultative lagoon. A flow diagram of the process is presented in Figure 1.

Literature data focused on landfills for small municipalities was used to calculate the inventory for the processes considered in Figure 1, given that the goal of this study is to provide a general landfill model. However, if primary data is available, the methodology here presented can also be used to estimate the inputs and outputs, which would help to provide a more reliable result in specific situations.
2.2.1 Waste transport to landfill
The first stage considered is the waste transportation from the urban center to the landfill. The exclusive use of trucks (3.5 tones of load capacity) and the way-and-back distance was estimated to be 15 kilometers, which was considered to be a reasonable distance for a small municipality. The emissions related to the transport were reported within the software in the unit tkm – that includes the mass transported (in tones) and the distance travelled (in kms).

2.2.2 Waste spreading and compactation
These emissions refer only to the operation of the landfill, specifically to the stages of waste spreading, compacting and covering. The diesel consumption was taken into account according to Rodrigues et al. (2008), which measured the average use in a municipality with 25,000 inhabitants and the atmospheric emissions due to the diesel burning in the dump truck and the bulldozers used in the landfilling and covering of the waste [13, 14].

2.2.3 Methane generation
The methane production was calculated according to the degrading of biodegradable matter present in the solid waste. The estimated percentage of organic matter in brazilian MSW is 50% and 60% average moisture content. A 60% destruction of volatile solids (VS) in this MSW during landfilling is stated under a density of 237 kg.m$^{-3}$, following the production of 0.25 m$^3$ CH$_4$.kg VS$^{-1}$ [15]. It’s then possible to calculate the biogas volume, considering the average methane content of 55% [16].

2.2.4 Direct air emissions
It was considered that 50% of the biogas produced was not captured by the drainage system, therefore released as direct emissions to the atmosphere [17, 18]. The biogas characterization presented in Tchobanoglous et al. (1993) was used, as it is in accordance with national experiences [16, 19].

2.2.5 Flaring emissions
A 50% efficiency was also considered for the flaring [20]. The losses were taken into account as methane emissions and the emissions deriving from the burning were based in the emission factors presented in Beylot et al. (2013) [21].

2.2.6 Leachate production
The software ‘Water surplus for sanitary landfills’ provided by the Brazilian National Institute of Meteorology (INMET) was used to estimate the leachate volume produced in small-sized landfills [22]. It was observed that in most simulations the water surplus represented approximately a quarter of

![Figure 1: Landfilling flows diagram](image-url)
local precipitation, so this percentage was used. This rate is also in accordance with the estimations proposed by the Swiss method of leachate prediction, based on the degree of compaction of the waste is its specific weight [23].

A mean annual precipitation of 1,500 mm was considered, disregarding other contributions and losses. The Environmental Company of the State of São Paulo (CETESB) indicates that for small municipalities the construction of the landfill using ditches is acceptable and even advised, so a depth 3 m for the ditches was estimated [24]. Using this data and the waste specific mass of 1.05 ton.m\(^{-3}\), the necessary surface for landfilling a ton of waste would be 0,317 m\(^2\). The water surplus of 375 mm (25% of the average precipitation considered) produced 0,375m\(^2\) of leachate for every m\(^2\) of landfill, or 0,119 m\(^3\) of leachate per ton of waste landfilled.

2.2.7 Leachate treatment and emissions

The emissions to water refer to the leachate produced in the landfill after treatment in an Australian lagoon system (composed of an anaerobic lagoon, with a height of five meters and followed by a facultative lagoon, with a height of two meters), which is commonly used in the country. The large amplitude observed in the leachate composition data in national landfills led to the adoption of values related to a real landfill, located in the State of Minas Gerais, aged 1,7 years. A sanitary landfill with an approximate age of two years was considered since it is believed that, under Brazilian climatic conditions, landfills of that age are already close to stabilization in terms of biodegradability [25].

The efficiencies found in the treatment of the treatment ponds indicated values well above those proposed by von Sperling (2014) for the Australian lagoon system [26]. Dias (2012) shows in her research that the water retention time of the leachate in the real landfill was high, arriving, at some times of the year, to a value 15 times greater than the one of design, and discusses that this situation is common in the country [25]. In view of this uncertainty and in search of greater significance for the simulated landfill, it was chosen to follow the efficiencies suggested by von Sperling (2014), for the system which, although originally developed for domestic sewage treatment systems, has been a reference for leachate treatment projects.

The atmospheric emissions from the treatment of leachate were considered according to the International Panel on Climate Change (IPCC, 2006), which reports them in the form of methane emission \[\text{These emissions are presented as a function of the BOD removed by the systems (in kg BOD), pond height and maximum methane production capacity for domestic sewage (0,6 kg CH}_4 . \text{kg BOD}^{-1}\].

3 Life Cycle Inventory of the Sanitary Landfill

Table 1 presents the Life Cycle Inventory of the modeled sanitary landfill. The table refers to the landfilling of 1 ton of MSW.

| Table 1: Life Cycle Inventory for a sanitary landfill |
|-----------------------------------------------------|
| Process                              | Input/Output | Parameter               | Unit    | Value (t.waste\(^{-1}\)) |
|--------------------------------------|--------------|-------------------------|---------|-------------------------|
| Landfill transport                   | Input        | Solid waste             | ton     | 1,00                    |
|                                      |              | Distance                | km      | 15,00                   |
|                                      |              | Transport               | tkm     | 15,00                   |
| Landfill operation                   | Input        | Solid waste             | ton     | 1,00                    |
| (spreading/compating)               |              | Diesel                  | kWh     | 4,32                    |
|                                      | Output       | Biogas to flaring       | ton     | 75,00                   |
|                                      |              | Biogas as direct emission| ton     | 75,00                   |
|                                      |              | Leachate                | m\(^3\) | 0,38                    |
|                                      |              | CO - diesel burn        | ton     | 3,59E-06                |
|                                      |              | NOx - diesel burn       | ton     | 7,78E-06                |
|                                      |              | Particulate matter - diesel | ton | 7,78E-08               |
### Biogas direct emissions

| Input       | Output          | burn                  |
|-------------|-----------------|-----------------------|
| Biogas as direct emission | ton | 37.50                |
| CH₄         | ton             | 2.50E-02              |
| N₂          | ton             | 9.08E-04              |
| NH₃         | ton             | 2.27E-04              |
| CO          | ton             | 4.54E-05              |
| SO₂⁻        | ton             | 2.27E-04              |

### Biogas flaring

| Input       | Output          | ton             |
|-------------|-----------------|-----------------|
| Biogas to flaring | ton | 37.50            |
| CH₄ - leak before flaring | ton | 0.01            |
| NOₓ         | ton             | 6.51E-06         |
| CO          | ton             | 7.60E-06         |
| Particulate matter | ton | 2.45E-06         |
| SO₂ (as SO₂) | ton             | 8.00E-05         |

### Leachate treatment

| Input       | Output          | ton             |
|-------------|-----------------|-----------------|
| Leachate    | ton             | 0.38            |
| Treated leachate | ton | 0.38            |
| CH₄ leak    | ton             | 1.37E-05         |
| BOD         | ton             | 3.82E-05         |
| COD         | ton             | 9.12E-05         |
| TSS         | ton             | 1.77E-05         |
| N-NH₃       | ton             | 2.02E-05         |
| N-org       | ton             | 1.50E-06         |
| P           | ton             | 6.19E-07         |

## Discussions

The inventory in Table 1 was inserted in the software SimaPro and analyzed using the ReCiPe 2016 method. The impact categories were chosen based on which ones would better demonstrate the processes involved in landfilling, such as diesel usage, transportation, emissions to air and water. Finally, the chosen categories were global warming, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, and terrestrial and freshwater ecotoxicity. The results are presented in Figure 2.

As it can be seen in the graphs, the biogas leaks represent most of the impacts related to air emissions. The transport is responsible for the vast majority of the impacts related to ecotoxicity, which can be related to distance in which landfills are usually located. The potential impacts in eutrophication are mainly caused by the leachate treatment.
Figure 2 presents the comparison of the modeled landfill with the one present in Ecoinvent v3 (Municipal solid waste {RoW}| treatment of, sanitary landfill | APOS, U). According to the information available on the database, the process considers the technology available in Switzerland in 2000 and includes short-term emissions to air via landfill gas incineration and landfill leachate; burdens from treatment of short-term leachate in wastewater treatment plant, including WWTP sludge disposal in municipal incinerator; and long-term emissions from landfill to groundwater after base lining failure [28].

The differences between the potential impacts of the two processes are visible in the graphs. The destination of the by-products, especially of the sludge, is a big difference between the models. According to the studies of Dias (2013), the Australian lagoons system design, initially intended for the treatment of domestic sewage, function mainly as an evaporation tank, with no sludge production in the bottom of the lagoon [25]. Sludge treatment, therefore, was not considered.

Figure 3: Comparison between the landfill modelled and one available in Ecoinvent 3
5 Conclusion
This work presented a model of a sanitary landfill that would correspond better to the reality of developing countries, especially in Latin America, aiming to improve the reliability of LCA studies. The life cycle inventory is based on average Brazilian data and literature data concerning the processes considered, focused on sanitary landfills for small municipalities. The methodology is adaptable to specific cases and can also be used with primary data to estimate emissions and environmental impacts.

When compared to a landfill available in the LCA database Ecoinvent v.3, based on European data, differences between the two could be observed. Regarding, fine particulate matter formation, terrestrial acidification, eutrophication and terrestrial and freshwater ecotoxicities, the difference in potential environmental impacts was greater than 80%. As for global warming, the difference was around 30%. These observations illustrate disparities between waste management technologies and how the usage of either systems can shift the conclusions of an environmental study, reaffirming the need of a representative model to estimate the environmental impacts of such technologies.

6 Recommendations
- Collection and use of primary data over literature data to improve the significance of the model.
- The consideration of leachate leaks to groundwater and soil.
- Obtaining regionalized data for the study site.

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