R. Latino-amer. em Aval. do Ciclo de Vida, Brasília, v. 2, n. 1, p. 91-121, jan./jun. 2018

Life cycle impact assessment of the municipal solid waste management system: a case study in a municipality in southern Brazil

Análise de impacto no ciclo de vida de um sistema de gerenciamento de resíduo sólido municipal: estudo de caso em um município no sul do Brasil

Análisis de impacto de ciclo de vida del sistema de gerenciamiento de residuos sólidos municipales: un estudio de caso en una municipalidad del sur del Brasil

Submetido em 10 de março 2018
Aceito em 29 de outubro 2018
Disponível em 22 de fevereiro de 2019

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Abstract

The present study conducted a Life Cycle Assessment evaluation of the Solid Waste Management System in Santa Cruz do Sul – RS, in order to provide background information and therefore support decision-making for future waste management scenarios. The software package named as Integrated Waste Management – 2, Version 2.5., was used to perform the LCA, where all inputs and waste management system outputs were identified and quantified. The conversion of the results from Life Cycle Inventory to Life Cycle Assessment in environmental impacts was carried out based on impact characterization factors from RECIPE 2008 version 1.08. The impact categories studied were: Photochemical Oxidant Formation Potential, Global Warming Potential, Acidification Potential, Eutrophication Potential, Depletion of the Ozone Layer Potential and Particulate Matter Formation Potential in addition to the Use of Energy and Final Solid Waste. The current waste management scenario has *been simulated as baseline, considering three additional scenarios, which included raising the number of households served by selective collection, improvement of recycling recovery efficiency in the sorting stage and the introduction of the biological treatment stage into the system by composting the organic matter. The results showed that the current scenario is the most impacting, for global warming, with a total of 12,102,122.85 kg of emissions per year, whereas scenario 04 showed to represent the lowest contribution rates to environmental impacts in carbon footprint perspective (5,946,702.47 kg of emissions per year). The final disposal stage in landfills had also contributed significantly to environmental impact rates, followed by the waste collection scenario. The proposed changes, suggested by alternative scenarios, had demonstrate considerable environmental savings, hereby justifying the importance of implementing these strategies in waste management.*

Keywords: *Life Cycle Assessment. Environmental Impact. IWM-2. Solid Waste. Brazil*

Resumo

Este trabalho desenvolveu um estudo de Avaliação do Ciclo de Vida de um Sistema de Gerenciamento de Resíduos Sólidos na cidade de Santa Cruz do Sul-RS a fim de dar suporte a tomada de decisões para futuros cenários de gestão de resíduos. Para executar a Análise de Ciclo de Vida, foi utilizado o software Gerenciamento Integrado de Resíduos – 2 (IWM-2), Versão 2.5. Neste programa, as entradas e saídas referentes ao inventário do sistema de gerenciamento foram identificadas e quantificadas. A conversão dos resultados do Inventário de Ciclo de Vida para Análise do Ciclo de Vida em impactos ambientais foi realizada baseada na caracterização dos fatores de RECIPE 2008, versão 1.08. As categorias de impacto estudadas foram: Potencial de Formação de Oxidantes Fotoquímicos, Potencial de Aquecimento Global, Potencial de Acidificação, Potencial de Eutrofização, Potencial de Depleção da Camada de Ozônio e Potencial de Formação de Material Particulado além do Uso de Energia e Resíduos Sólidos Finais. O atual cenário de gerenciamento de resíduos foi simulado como base, considerando três cenários adicionais, os quais incluíam o aumento do número de famílias atendidas por coleta seletiva, melhoria na eficiência de recuperação da reciclagem na fase de triagem e introdução do estágio de tratamento biológico no sistema por compostagem de matéria orgânica. Os resultados mostraram que o cenário atual é o mais impactante para aquecimento global, com um total de 12,102,122.85 kg de emissões por ano, enquanto que o cenário 04 apresentou menores taxas de contribuição para esta categoria (5,946,702.47 kg de emissões por ano). A etapa de disposição final em aterros também contribuiu de forma significativa para a variação de impactos ambientais, seguido pela etapa de coleta de resíduo.

As alterações propostas, sugeridas pelos cenários alternativos, demonstraram consideráveis melhorias ambientais, justificando a importância da implementação destas estratégias no gerenciamento de resíduos.

Palavras-Chave: *Análise do Ciclo de Vida. Impacto ao Meio Ambiente. IWM-2. Resíduo Sólido. Brasil*

Resumen

Este trabajo presenta los resultados del Análisis de Ciclo de Vida del Sistema de Gestión de Residuos Sólidos de la ciudad de Santa Cruz do Sul-RS-Brasil, para apoyar la toma de decisiones para futuros escenarios de la gestión de residuos. Para realizar el ACV fue utilizando el software de IWM, versión 2.5. En este programa, las entradas y salidas relativas al análisis del inventario fueron identificadas y cuantificadas. La conversión de los resultados del Inventario para la evaluación de los impactos se hizo con base en los factores de conversión RECIPE 2008 Versión 1.08. Las categorías de impacto estudiadas fueron: Potencial de formación de oxidantes fotoquímicos, calentamiento global, de acidificación, de eutrofización, de agotamiento de la capa de ozono, formación de material particulado, consumo de energía y los residuos sólidos final. El escenario actual fue simulado como valor de referencia. Otros tres escenarios fueron estudiados, los cuales incluyen el aumento del número de hogares con servicio de recogida selectiva de residuos, el aumento de la eficiencia de la etapa de separación de materiales reciclables y la introducción de la etapa de tratamiento biológico en sistema por medio del compostaje de la materia orgánica. Los resultados mostraron que el escenario actual es el más impactante en relación al potencial de calentamiento global, con un total de 12.102.122,85 kg equivalentes de CO2 de emisiones por año, mientras que el cuarto escenario mostró contribuciones más bajas para esta categoría (5.946.702,47 kg equivalentes de CO2 de emisiones por año). La etapa de la disposición final también contribuyó significativamente con los impactos ambientales, seguido de la etapa de recolección de residuos. Las modificaciones sugeridas y simuladas por los escenarios alternativos mostraron mejoras ambientales considerables, lo que justifica la importancia de implementar estas estrategias en la gestión de residuos.

Palabras Claves: *Análisis del Ciclo de Vida. Impacto al Medio Ambiente. IWM-2.5. Residuo Sólido. Brasil*

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1. Introduction

Municipal Solid Waste (MSW) represents social and environmental problems the society. The disastrous consequences of incorrect waste management are sufficient to alert the public interest in the need to adopt public policies that seek to reverse this situation. Particularly, waste management is a method directing managements and/or institutions to acting for sustainability by displaying their ability to use and protect current resources (Goulart Coelho and Lange, 2016).

The proper management of solid waste is a major challenge for large urban centers in Brazil and Latin America recently. In developing countries, the health and environmental implications related to solid waste management are urgent. MSW becomes an important issue for cities in emerging economies due to the high costs associated and to the lack of understanding over the factors that affect the different stages of MSW (Goulart Coelho and Lange, 2016). Over the past two decades, various actions and designs have been proposed for improving the treatment and disposal of municipal solid waste (Reichert and Mendes, 2014). The approval of Law 12.305 (Brasil, 2010) has supported a comprehensive guideline to lead Brazil towards a more sustainable waste management system.

The NSWP (National Solid Waste Policy) aims to boost other forms of treatment and final disposal, and Landfills represent one of these alternatives. It is essential that the priority order of MSW defined by NSWP is: no generation; reduction; reuse; recycling; treatment; and finally, final disposal (Brasil, 2010). This is often referred as waste hierarchy in order to treat MSW: Waste prevention, re-use, recycling, waste-to-energy and landfill as the latest option. Even recognizing that landfills are designed to protect the environment against potential burdens, there are several disadvantages as follow: High amount of methane, mostly emitted directly to atmosphere or trapped inside the landfills cells; Risk of leachate leakage causing pollution to water resources; and the lack of available physical space for landfills close to urban dense areas (Agostinho et al., 2013). Therefore, different alternatives for the management of MSW should be considered and evaluated to avoid disposal in landfills, taking into account environmental, economic and social parameters.

Due to the undesirable effects of landfill gases, the generation of slurry and the occupation of territory without the use of materials, composting has become one of the alternatives to landfills, as a form of waste recovery (Hong et al., 2010). By composting - Aerobic decomposition by microorganisms - it is possible to transform the organic portion of the waste, creating a product useful as a soil fertilizer. Due to its advantages, this technique has been included as a potential management stage of MSW. Recycling is also being suggested as a better alternative for waste management, in which different technological processes are currently available for MSW sorting and recycling (Agostinho et al., 2013). Numerous international studies have shown that the recycling of waste materials can result in net savings of GHG emissions. According to Turner et al. (2015), this is because recycling materials into new (secondary) products can displace production of primary products that may require significant inputs of energy and raw materials.

Reichert and Mendes (2014) states that the management of municipal solid waste, depending on the different alternatives and techniques used to handle, transport, process, treat and dispose of waste has the potential to generate environmental impacts resulting from gaseous emissions, liquid and final waste of the various stages of the management system. In order to provide this technical background, the Life Cycle Assessment Tool (LCA) is a concrete possibility. The life cycle thinking concept and quantitative tools such as LCA can provide a science-based support to a more environmentally sustainable decision-making in waste management (Goulart Coelho and Lange, 2016). Therefore, the LCA method can play a critical role in decision support through providing a comprehensive assessment of the environmental impacts of alternative waste management systems (Komakech et al., 2015).

Because of the current change in the landscape of MSW management in Brazil, in particular with the introduction of Law 12.305 (Brasil, 2010), National Solid Waste Policy, a more in-depth study of the current management system of municipal solid waste in the municipality of Santa Cruz – RS is needed. Therefore, this study aims to conduct an environmental assessment of the Municipal Solid Waste Management System of the city.

2. Materials and methods

2.1. Study Location

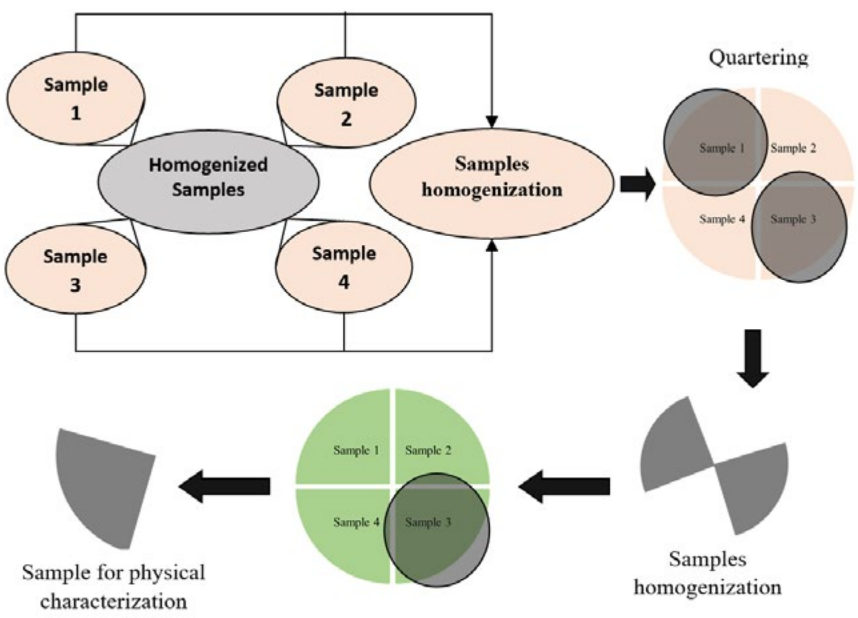
The case study was conducted in the city of Santa Cruz do Sul, which is situated in the center of Region of the Vale do Rio Pardo and Taquari Valley, in the state of Rio Grande do Sul, Brazil, characterized as the hub city among the 47 municipalities that make up these regions. Being 73.00 meters of altitude above sea level, Santa Cruz do Sul is located at latitude 29º43’04” South and longitude 52º25’33” West. The city has 118,374 inhabitants, with 105,184 inhabitants in the urban area, which corresponds to 88.9% of the total population and 13,103 inhabitants in rural areas, making up 11.8% of the total population. The urbanization rate is 89.4% and the population density is 161.4 hab./km (IBGE, 2010).

2.2. Current Diagnosis

The relevant data has been assessed through surveys and research with the City of Santa Cruz do Sul and the Collectors and Recyclers Cooperative of Santa Cruz do Sul – COOMCAT. Physical characterization of the municipal solid waste (MSW) was also performed.

The physical characterization of MSW was determined using the quartering technique (ABNT, 2004). Representative samples of waste were collected, and these were analyzed to identify the waste components. The process included composite sampling, and sampling was carried out in duplicate for each route, on different days, including all of the waste collection routes. Trucks from different neighborhoods transported the waste to a temporary disposal, in a place previously authorized by the city government. These samples from different neighborhoods were mixed to obtain a homogeneous waste sample, which was divided into four equal parts (i.e. quartering).: Two opposite diagonal portions were selected to be homogenized again, whereas the two remaining parts were discarded. In the resulting sample the same quartering process was applied to yield a sample of approximately 1,00 m³ of waste, as shown in Figure 1.

Figure 1. Quartering process.



After obtaining the desired sample, the manual separation of the components was performed by dividing the waste into six groups: Paper/

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Cardboard; Plastic (hard plastic and soft plastic); Metal (ferrous and non-ferrous); Glass; Organic matter; and rejected waste. These were packed into 200-liter plastic pails and weighed individually, thus allowing the calculation of the individual percentages of each waste group.

In order to conduct the gravimetric composition study of the municipal solid waste, the activities described above were repeated for five days, and cover all trash collection routes, thereby addressing collections in a variety of neighborhoods. These activities were carried out in two stages, comprising of two distinct seasons, between summer and early fall. The second stage was conducted in August, in winter season. The evaluation of these stages at different times of the year enabled to aggregate them in an average result perspective.

2.3. Definition of scope and functional unit

The scope of this paper considers the activities required to manage MSW from the time it is sent for collection to final disposal. Thus, the generation of stages, transport, storage, treatment and disposal were analyzed and quantified, taking into account the balance of materials, energy, air emissions and waste (liquid and solid). This analysis and quantification considered the different stages of each of the proposed scenarios.

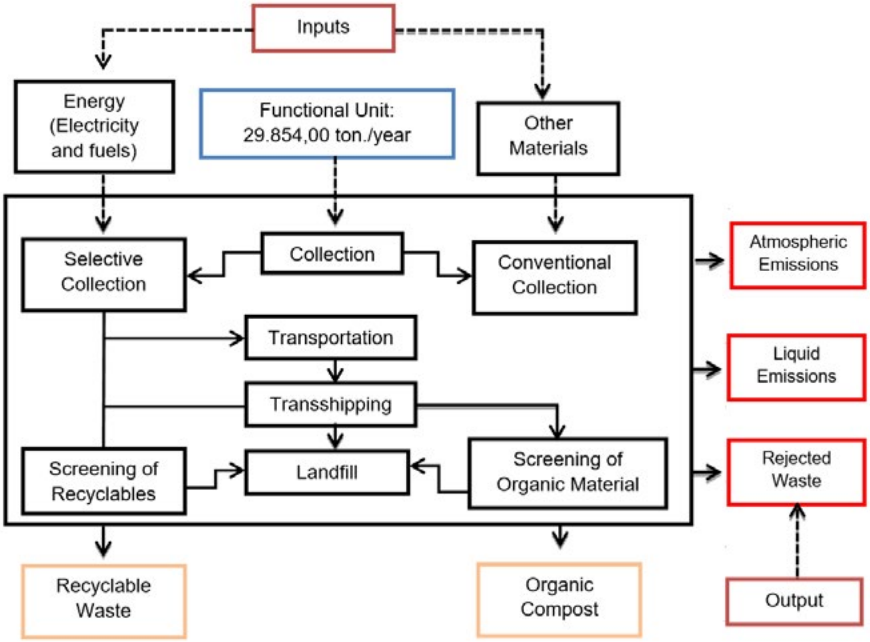
With regard to the treatment of waste, logistics surrounding the destination of recycled materials has not been determined, limiting only to the recyclable material ready for use. The scope was defined by the need to assess solely the local reality of the management system.

The functional unit used in this study is the annual MSW generation for the municipality (Dong et al., 2014; Fernández-Nava et al., 2014; Koroneos and Nanaki, 2012; Parkes et al., 2015; Rodriguez-Iglesias et al., 2003; Song et al., 2013). Thus, the daily generation of 81.8 tons is extrapolated for the annual quantification, equivalent to 29,854.00 tons. All emissions, energy consumption and materials are based on this functional unit. The inventory was conducted for each of the developed scenarios and used the assistance of IWM-2 software, version 2.5, for the development of the waste routes and quantification of inputs and outputs. The system boundaries are defined in the flowchart in Figure 2.

2.4. Application of Model IWM-2, Version 2.5

The LCA study was performed through IWM-2 model, version 2.5 developed by McDougall et al. (2001). LCA-IWM was specially designed for planning and optimizing waste-management systems in areas in which much effort is still required to achieve the state-of-the-art practices in waste management, as is the case for the city in study. The LCA-IWM methodology was adapted to the Brazilian waste context and to the local characteristics, which includes waste composition, electricity mix and national regulations (Goulart Coelho and Lange, 2016).

Figure 2. Limits and boundaries of the LCA study system.



In order to o set the conversion values obtained by the LCA on environmental impacts, we conducted simulations based on the impact characterization factors used by SimaPro® Software of Pre Consultants and published in the RECIPE 2008 report, version 1.08, with values revised in February 2013.

2.5. Scenarios analyzed and computational modeling

By obtaining the diagnosis of the current management situation, consisting of data and information from the years 2013 and 2014, the other three waste management scenarios have been simulated, which were created based on the requirements established by Law 12.305 (Brasil, 2010) and also the targets considered by (ICLEI, 2012). Targets for the year 2019, for the cities of southern Brazil are listed, for example:

• 50% reduction in the percentage of dry recyclable waste in landfills;

• 40% reduction in the percentage of wet waste in landfills.

2.5.1. Current Scenario (CS)

This scenario represents the current management of MSW in Santa Cruz do Sul - RS. The waste is bagged by the citizens of the city, collected, transported, sorted and rejected waste is sent to the transshipping area, and then sent to landfill. Currently the city has conventional collection (no differentiation between recyclable, organic waste and/or rejected waste), serving 100% of the population, and selective collection (collected recyclable waste: paper, plastic, metal and glass, and organic waste/rejected waste) in 09 neighborhoods, representing 25.00% of households. In addition, MSW management has a waste sorting stage suitable for recycling. 10320.00 tons/year of MSW is shipped for sorting, with an efficiency of 4.56% of removal of material.

The data presented in the sequence are introduced into the software. The total quantity generated, and gravimetric composition were not changed:

• Population served: 118,374 inhabitants;

• Number of people per household: 3.4 inhabitants per residence;

• Number of households: 34,816.00 homes;

• Average generation of MSW: 252.22 kg/inhabitant/year;

Regarding the composition of the waste input data to the software, Table 1 presents the values considered.

Table 1. Parameters considered for introduction into the software - Waste composition.

Papers	Glass	Metal	Plastics	Textiles	Organic	Other
9.9%	3.0%	2.0%	13.5%	0%	41.7%	29.9%

Regarding the composition of the materials in the selective collection stage and sorting stage, Table 2 shows the values considered. Note that in this item the quantities of material are expressed in kg/household/year, i.e. the weight in kilograms of materials generated annually in each house of the region studied.

Table 2. Composition of materials considered for entry into the software for the stages of selective collection and sorting, expressed in kg/household/year.

Stage	Paper	Glass	Ferrous metals	Non-ferrous metals	Hard film	Hard plastic	Textiles
Selective collection	32.9	0.2	2.6	0.3	0.0	4.9	0.0
Sorting	6.4	0.8	0.0	0.8	0.0	4.9	0.0

2.5.2. Scenario 02 (S2)

Scenario 02 shows an increase in the weight of material collected in the selective collection stage and improvement in the efficiency of obtaining materials suitable for recycling in the MSW in the sorting stage.

Selective collection works specifically with the collection of paper, plastic, metal and glass.

Table 3 presents the information regarding the conventional collection systems and selective sorting, transfer of data, landfill and recycling. The available data, as shown in Table 3, was defined according to the IWM-2 software. Furthermore, they also represent information obtained by collection data from the waste management system.

Table 3. Parameters considered for introduction into software.

Parameter	Value considered
Number of households served by conventional collection	34,816.00 homes
Number of households served by selective collection	8,704.00 homes
Total consumption of diesel in all stages of management	9,96 Liters/ton.
Number of households served by selective collection	5.0 kwh/ton.
Diesel consumption in the sorting stage (all scenarios)	1.0 Liter/ton.
Natural gas consumption	0.1 m^3/ton.
Distance from the sorting plant to the landfill (all scenarios)	215 km (round trip truck)
Percentage of materials transferred to the landfill after sorting (all scenarios)	100%
Diesel consumption in transshipment step and transport to landfill (all scenarios)	0.9 Liter/ton.
Electricity consumption in the transshipment stage (all scenarios)	0.2 kwh/ton.
Electricity consumption at the landfill (all scenarios)	1.6 kwh/ton.
Diesel consumption at the landfill (all scenarios)	2.0 Liter/ton.
Biogas collection efficiency (all scenarios)	90.0%
Energy recovered from biogas (all scenarios)	0.0%
Slurry collection efficiency (all scenarios)	100.0%
Slurry treatment efficiency (all scenarios)	95.0%
Transport distance of the recyclable materials form sorting unit to the recycling unit	Considered local recycling

In the sorting stage of MSW, we will process the improved efficiency, i.e., a greater amount of material obtained and sent for recycling. Currently 10,320.00 tons/year of waste are sent for sorting, and only 311.52 tons/year of recyclable materials are recovered, which corresponds to 4.56% efficiency. This scenario suggested to increase this efficiency to 55.31%. This value is equivalent to 5,707.99 tons/year of recyclable materials being recovered, i.e., 23.78 tons/day. Table 4 lists the parameters considered for introduction into the software.

Table 4. Parameters considered for introduction into the software - Scenario 02.

Parameter	Value considered
Number of households served by selective collection	17,408.00 homes
Diesel oil consumption (only selective collection stage)	16,045.7 Liters/year
Total consumption of diesel oil (all stages of management)	313.539,23 Liters/year

2.5.3. Scenario 03 (S3)

Scenario 03 represents the introduction of biological treatment of organic waste by composting. In order to avoid the disposal of wet waste in landfills, a factor of 40% has been suggested (ICLEI, 2012). Then, this scenario includes the stages of MSW collection, transport, sorting, biological treatment by composting, transshipment and final disposal in landfill. The stages involved in the management of MSW in scenario 03 are similar to scenario 01 (S1).

The specifications of the input parameters for the software follow the same values listed in Table 3, scenario 01. Table 5 presents the values for the biological treatment.

Table 5. Parameters considered for introduction into the software - Scenario 03.

Parameter	Value considered
Electricity consumption in composting	40 kWh/ton.
Weight reduction in composting	50.0%

2.5.4. Scenario 04 (S4)

Scenario 04 lists the targets proposed in scenarios 02 and 03 in the same MSW management system. In this way, the targets are considered to have a 25.00% increase in the weight of collected materials in the selective collection stage and composting 40% of the organic matter from MSW sorting stage.

The parameter specifications follow the same values listed in Tables 3 and 4, of the previous scenarios, since stage 04 interconnects the two alternatives, which have already been set apart.

2.6. Environmental Impact Analysis

From the development of the scenarios and their inventories, methodologies will be used to conduct the assessment of environmental impacts caused by MSW management. The proposed methodology enables an analysis for the LCA according to ISO 14040 (ISO, 2006) requirements. This methodology considers the following categories of impact assessment, and their respective units: Photochemical Oxidant Formation Potential (kg NMVOC/year); Global Warming Potential (kg CO2 Equiv./year.); Acidification Potential (kg SO2 Equiv./year.); Eutrophication Potential (kg PO4 Equiv./year.); Ozone layer Depletion Potential (kg CFC-11 Equiv./year.); Particulate Matter Formation Potential (kg PM10 Equiv./year). In addition to these six (06) categories, the indicators will be presented referring to the “energy use” and “final solid waste” for each of the scenarios analyzed.

3. Results and discussions

3.1. Generation and gravimetric composition of MSW

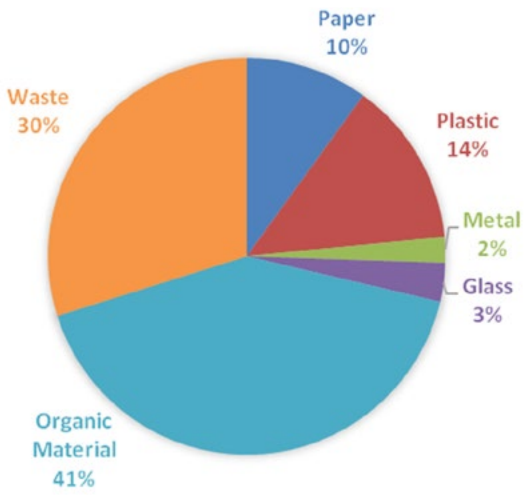
Currently, waste is collected in the urban area and rural area of the municipality, about 81.8 t / day. After, it is sorted and transported to disposal in landfill properly regularized in the city of Minas Leão – RS. Table 6 shows the evolution of MSW generation in the last 03 years.

Table 6. Evolution of the MSW generation in the city of Santa Cruz do Sul in the last three years.

Year	Quantity (ton./day)		Total Quantity (ton./month)		Quantity (ton./day)	Total Quantity (ton./year)
	Urban Area	Rural Area	Urban Area	Rural Area		
2011	67.76	2.57	2,032.80	77.10	70.33	25,670.45
2012	73.07	3.59	2,192.10	107.70	76.66	27,980.90
2013	76.50	5.30	2,295.00	159.00	81.80	29,854.00

Note that there was an increase of approximately 14.00% in MSW generation in the period between the years 2011 and 2013, and the population in the same period increased by approximately 5.00%. The per capita MSW generation currently is 0.69 kg/inhab./day. This value is shown above in the rates stated in CETESB (2009), in which the average per capita generation is 0.5 kg/inhab./day for municipalities with populations between 100,001 and 200,000 inhabitants. It is noteworthy that the municipality of Santa Cruz do Sul generates a large amount of MSW daily, and these values have increased considerably in recent years. Figure 3 shows the values obtained for the gravimetric composition of Municipal Solid Waste.

Figure 3. Characterization of average gravimetric composition of MSW in Santa Cruz do Sul.



3.2. Energy Use and Solid Waste sent to Landfill

This indicator includes all consumed energy values and energy values generated in the MSW management system, as well as the solid waste quantities sent to Landfill (Table 7). Energy consumption considers the use of electricity, fossil fuels (diesel, for example) and natural gas.

The stages that contribute most to energy use are landfill and collection, respectively, which represent the highest energy consumption rates, mainly due to diesel consumption, the fuel used for the trucks that collect and transport transshipment waste to the landfill.

Bezama et al. (2013) conducted a study in Chilean Patagonia, where they observed a variation in energy use, in different stages of MSW management, which ranged from approximately 20.00 kWh/ton. to 60.00 kWh/ton. of waste collected and sent to landfill. Pressley et al. (2014), determined that the energy consumed by the equipment, facilities and vehicle fuel corresponds to 4.4 GJ/Mg of waste collected. A study by Rodriguez-Iglesias et al. (2003), evaluated different situations of MSW management and energy use was between 33,000,000.00 GJ/year and 48 million GJ/year. In this same study, the authors state that the reduction in the generation of solid volumes provides a discount of 30% in energy use. The implementation of composting has the highest levels of energy use and the reduction of the distances to the MSW treatment plants does not represent a significant improvement in overall energy use.

Table 7. Energy use and Final Solid waste sent to landfill.

Scenarios	CS	S2	S3	S4
Energy Use (GJ/year)	28240	-5881	6980	-16353
Final Solid Waste (tons/year)	29242	26175	17544	15718

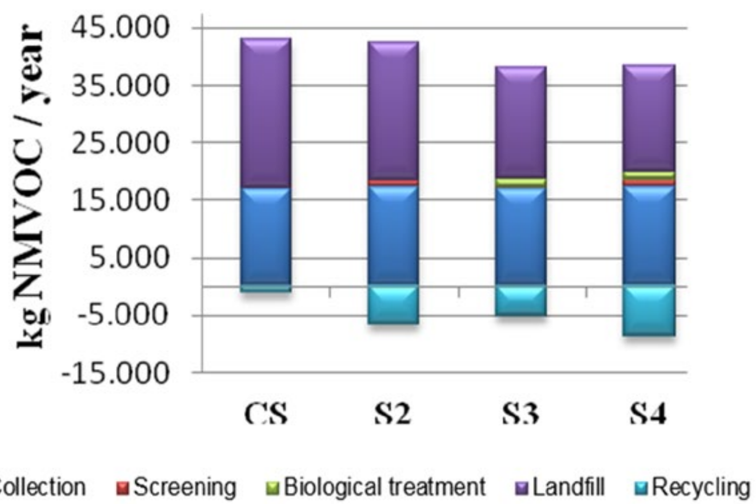
Table 07 also reinforced the importance of increasing recyclable recovery percentage, as well as the introduction of biological treatment by composting organic matter, in order to avoid the landfill disposal of waste. These potential improvements in efficiency and organic matter reutilization decrease the amount of MSW sent to landfill by 46.24%. In the present scenario 29,242 tons of waste per year is sent to land fill as the final destination, whereas it reduces to 15,718 tons per year, in scenario 04.

3.3. Environmental impact Assessment

3.3.1. Photochemical oxidant formation potential

This indicator defines the substances that have the potential to contribute to the formation of photochemical ozone, and volatile organic compounds (VOCs) containing hydrogen (not fully substituted) and / or double (unsaturated) bond(s) (Hauschild and Wenzel, 1998). Rigamonti et al. (2009) state that it represents the substances that cause photochemical ozone production in the troposphere. Figure 4 presents the analysis of the contributions of each stage involved in the management of MSW in the 04 scenarios studied.

Figure 4. Environmental performance for the MSW scenarios: Photochemical oxidant formation potential.



The analysis shows that collection and landfill stages are the largest contributors in the 04 scenarios. A study by Erses Yay (2015), found similar results, where the collection and disposal of waste in landfills showed the highest emission rates, especially methane. Emissions from the MSW collection stage remain constant over the 04 scenarios. Improved sorting efficiency brings with it an increase in pollutant contribution, but this increase appears to be negligible compared to the environmental benefits produced from the recycling of recovered materials. The biological treatment of organic matter also brings with it the generation of pollution load, but this stage helps to reduce the amount of materials sent to the landfill, causing a decrease in the pollution, as seen in scenario 03 and scenario 04.

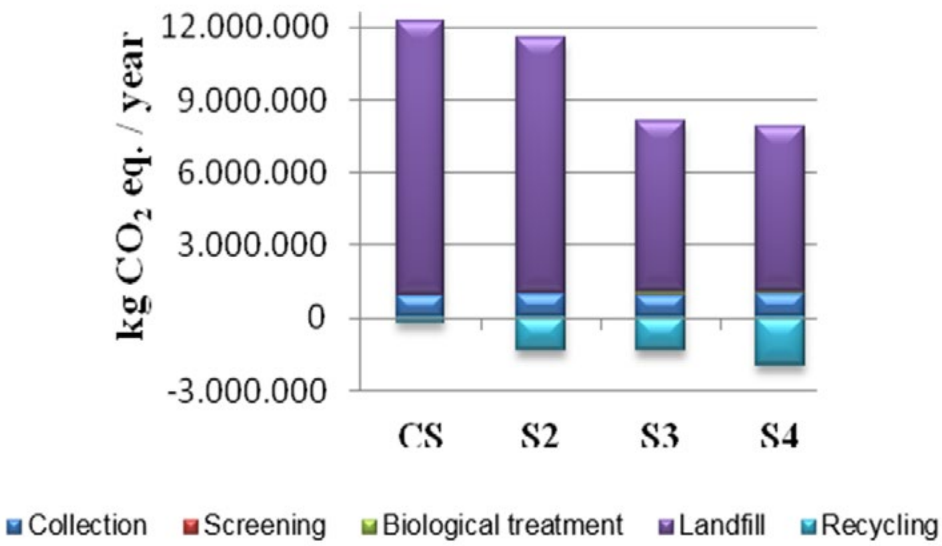
In all scenarios, waste disposal in landfill is the stage with the largest emissions contribution in this category. In the baseline analysis, 25,981.09 kg NMVOC equiv./year are released, whereas in scenario 04 this number is reduced to 18,621.94 kg of NMVOC equiv./year, representing a decrease of 28.32% of emissions. This reduction is mainly due to improved material recovery efficiency of waste suitable for recycling and the introduction of the organic matter composting stage, which represented a decrease in the quantities of waste sent to landfill.

Gunamantha and Sarto (2012) conducted a study in Indonesia, which compared some waste management options. In one of the options, the waste was collected and sent to landfill. The authors determined that this scenario sends 0.3898 kg C_2H_4 equiv./ton. of waste, and the landfill stage is the main contributor. Bovea et al. (2010) found values close to 0.10 kg C_2H_4/uf and up to 0.16 kg C_2H_4/uf in a study conducted in Spain, using a functional unit of 1.00 ton.

3.3.2. Global warming potential - GWP

The PAG, according to Rigamonti et al. (2009) is the indicator of gas emissions causing the greenhouse effect. According to Zaman (2013), global warming may be caused by the disposal of waste, as it contains harmful gaseous by-products and particles that can increase greenhouse gases. The category of global warming considers the CO2 parameters (fossil and renewable), CH4 and N2O measured as CO2 equivalent, and these emissions occur mainly during the breakdown of final waste. Figure 5 demonstrates the contribution of environmental impact as related to the PAG.

Figure 5. Environmental performance for the MSW scenarios: Global warming.



There is a notable reduction in emissions when comparing the current scenario and scenario 04 where 40.36% of CO2 is released into the atmosphere. This is mainly due to the decrease of waste, especially organic matter that is sent for biological treatment, to be deposited in landfills. According to Bovea and Powell (2006), the impact of contribution that occurs in landfills is a direct consequence of emissions of the gases generated, mainly CO2 and CH4. A study by Banar et al. (2009), showed that CH_4 had the most impact for the landfill stage.

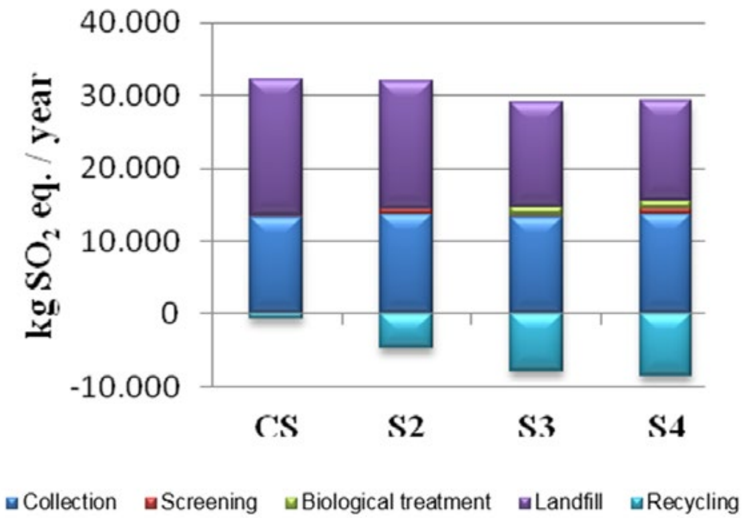
According to the Intergovernmental Panel on Climate Change (IPCC, 2001), it is estimated that the CH_4 produced in solid waste disposal sites contributes about 3.0 and 4.0% to annual global anthropogenic emissions of greenhouse gases. Studies by other authors expressed varying values for emissions for the PAG. For example, Miliute and Kazimieras Staniskis (2010) analyzed the landfill option for waste generated in the Alytus region (Lithuania). They considered a total generation of 45,150 ton./year of MSW, obtaining a value of 51,230.00 tons of CO_2 equiv. (1.135 kg CO_2 equiv./ton. of waste) for this impact category. Mendes et al. (2004) had a value of about 900.00 kilograms of CO_2 equiv./ton. of waste for this category of impact when analyzing the solid waste landfill in the city of São Paulo, Brazil. Gunamantha and Sarto (2012) obtained a value of 188.00 kg CO_2 equiv./ton. for a similar study corresponding to three cities in the Yogyakarta region in Indonesia.

3.3.3. Terrestrial Acidification Potential

Emissions of potentially acidifying substances, when deposited, can cause damage to plants and animal populations (Arena et al., 2003). The acidification potential is defined as the number of H^+ ions produced per kg of substance on the SO_2. Rigamonti et al. (2009) relates the potential of acidification with the emissions of NO_X, SO_X and ammonia.

Figure 6 shows the contribution of impact by acidification in different stages of the 04 scenarios analyzed. The environmental impact of acidification is displayed mainly in the stages of collection of MSW and final disposal in landfill. Bovea and Powell (2006) point out that the contribution of this category is due to the fuel consumption associated with the stages of collection and transportation to final treatment.

Figure 6. Environmental performance for the MSW scenarios: Terrestrial acidification.

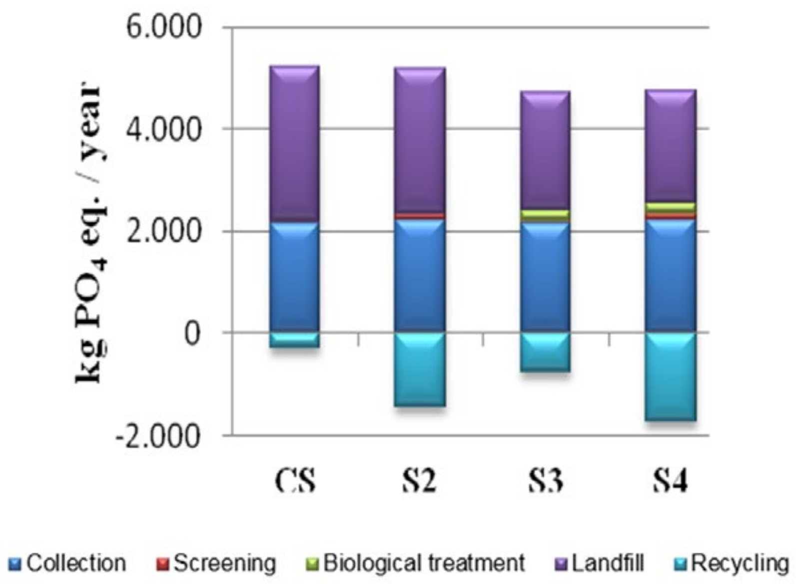


The recycling of materials provides environmental gains, i.e. harmful substances are no longer released into the environment. Özeler et al. (2006) found in a study conducted in the city of Ankara, Turkey, the environmental impacts related to acidification decrease with increased recycling of dry materials. Bovea and Powell (2006) noted in their study, which favors recycling significantly reducing the environmental impact, reaching the equivalent of -2.00 kg of SO2 for alternative processes, while the pattern of impact of the other stages together comes to, at most the equivalent of 0.5 kg of SO2.

3.3.4. Eutrophication Potential

According Tarantini et al. (2009), the potential impact for eutrophication is mainly due to high concentrations of nitrates and ammonia present in the landfill slurry, even if the waste is properly treated in the Treatment Plant. Reichert and Mendes (2014), states that eutrophication concerns the potential impacts related to the excessive concentration of nutrients, especially nitrogen and phosphorus. Figure 7 shows the impact of eutrophication contribution in the various stages of each of the scenarios.

Figure 7. Environmental performance for the MSW scenarios: Eutrophication.



The landfill stage appears as the main contributor to this category, emitting 3,048, 41 kg of PO4 equiv./year in the current scenario and 2,220, 75 kg of PO4 equiv./year. A decrease of 27.15% is evident in emissions at this stage. Tarantini et al. (2009), point out in their study the generation of just over 3,000.00 kg of PO4 equiv./year for the landfill stage. Sorting and biological treatment are responsible for contributing very similar amounts of emissions, which represent minimum impact values. Even considering that the organic matter can be composted, some final elements of the process remain in the form of minerals, causing eutrophication, and therefore, the poisoning of the soil, air and water, as in the case of some metals and compounds not susceptible to biodegradation (Branco, 1989).

The use of materials through recycling provides environmental benefits in all scenarios studied, and in stage 04 the most positive in environmental terms, which are 1,718, 40 kg of PO4 equiv./year are left to be released into the environment.

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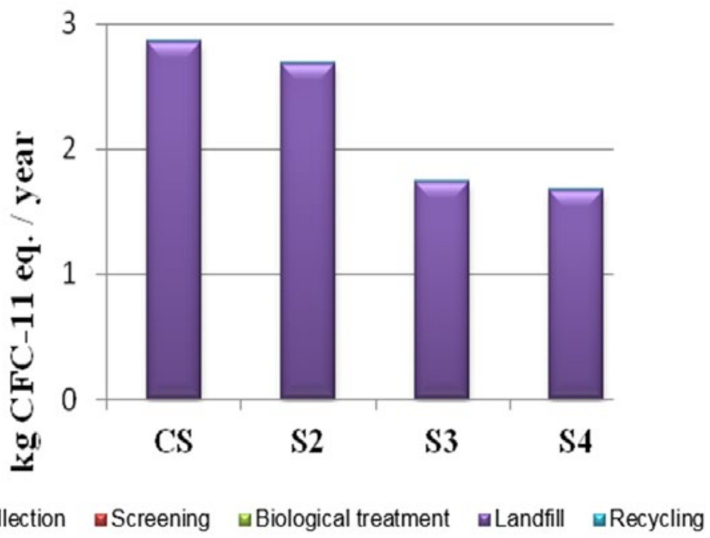
3.3.5. Depletion of the ozone layer potential

Chlorofluorocarbon (CFC-11) and its derivatives are the main agents in the depletion of the ozone layer. Gases of this nature, particularly those generated in landfills can contribute to the destruction of the ozone layer due to the presence of chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), in addition to increasing the risk of cancer (Wang et al., 2015). Figure 8 presents the contribution values for the indicators at each stage of MSW management.

Figure 8. Environmental performance for the MSW scenarios: Depletion of ozone layer.



By analyzing the values, it is clear that only the landfill stage contributes significantly to emissions. In the present scenario 2.86 kg of CFC-11 equiv./year are released into the environment and in stage 04, which showed a decrease of 41.95% of emissions, the value was 1.66 kg of CFC-11 equiv./year.

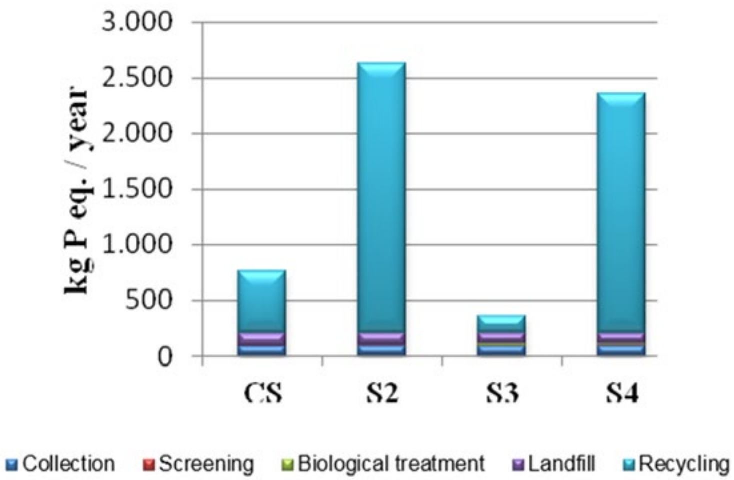
A study by Bezama et al. (2013), considered the construction of a landfill for disposal of MSW, the study found values that indicate the depletion of the ozone layer in the landfill stage. This may have been the result of waste products containing chlorofluorocarbons used in refrigerators and aerosols.

This same study determined that the emission of CO2 and CH4 produced by organic matter eliminated in landfills is an influential factor. In this study, the scenario considered sending only MSW to landfill, representing about 30% of emissions. In a study conducted in southern Brazil, Mangue et al. (2015), noted that the introduction of a landfill in the management of MSW allowed a decrease of 63.8% in the emissions related to this indicator.

3.3.6. Particulate matter formation potential

Under the general name of "Particulate Matter" is a set of pollutants made up of dust, fumes and all types of solid material and liquid that remains suspended in the atmosphere because of its small size. Particulate matter can also form in the atmosphere from gases such as SO2 - sulfur dioxide, NOx - nitrogen oxides and VOCs - volatile organic compounds, which are emitted mainly in combustion activities, turning into particles as a result of chemical reactions in the air (Quintanilha, 2009). Figure 9 shows the impact values obtained for each stage in the four scenarios to display Particulate Matter Formation potential.

Figure 9. Environmental performance for the MSW scenarios: Particulate matter.



Note that the landfill stage and collection of MSW stage have the greatest impact, respectively. The recycling stage, in all scenarios, brings with it a reduction in emissions, with a consequent reduction of environmental impacts.

In the landfill stage, we can see a reduction of 27.15% in the amounts of emissions. This is mainly due to the reduction of material being sent to landfill and the decreased fuel consumption by trucks that transport the waste to the final destination. In all scenarios recycling represented environmental gains, and in scenario 04, there are no more than approximately 5726.50 kg of PM-10 equiv./year.

Dong et al. (2014) conducted a study in China, which analyzed the current situation of MSW management, and two additional scenarios. In the first scenario, where the waste is sent to landfill without gas collection, it was observed that this contributes to 7.74E-05 kg of PM-10/ton. of collected waste. The second scenario analyzed, which is characterized as the current scenario, has the final disposal of MSW at landfills, but with the collection of gas with 70% efficiency ± 4% and production of electricity with 39.1% efficiency. This scenario contributes 3.44E-04 kg of PM-10/ton. of waste. In the third scenario, the option of waste incineration was selected with energy recovery (27% efficiency) and emission of 0.13 kg MP-10/ton. of waste.

4. Conclusions

The LCA study can help and contribute positively to the intensification of new projects aimed at reducing environmental impact, promoting the development of composting or equipping sorting plants for this stage to help them reach the established targets, for example.

The current scenario, which was completely characterized, has well-structured steps, but some details make the system unable to operate in the best possible way. Negative aspects were observed, such as flaws in the sorting

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stage, mechanical problems with equipment – conveyer belt of sorting table and front end loader - electrical system in the Sorting Plant was out of date and shortages of labor to carry out the waste sorting are some of the points observed that result in the excessive accumulation of waste in the area of Sorting Plants.

The physical characterization of MSW of the municipality made it possible to know the percentage of each material relative to the total waste generated - paper, plastic, metal, glass, organic matter and waste. Through this knowledge one can define the best treatment options to be implemented in the system, such as: recovery of recyclable materials, composting of organic material and disposal. Better separation of waste at the source is essential for these other stages to succeed and reach the expected efficiency.

The current MSW management scenario in Santa Cruz do Sul showed the worst environmental performance across all scenarios analyzed, since it presented the highest environmental impacts related to emissions to air and water, the increased use of energy and the largest quantities of waste being deposited in landfill.

Scenario 04 achieved the best performance, with smaller contributions from environmental impacts, lower energy use and the lowest amount of waste sent to the landfill.

The disposal of waste in landfill proved to be the most impacting stage of the MSW management system in the current scenario and the other three simulated scenarios. This stage involves the emissions from vehicles and machinery, the degradation of organic matter and the generation of slurry.

By increasing the coverage area of selective collection, improving the efficiency of the sorting stage and entering the biological treatment stage of organic matter, significant environmental benefits can be observed, in particular, reductions in energy consumption and pollutant emissions, as well as a decrease in the amount of waste sent to the landfill.

The results can be used to quantify the magnitude of potential growth in environmental performance related to decision-making in the MSW management system, making changes and / or improvements in transportation and final disposal possible.

Acknowledgements

The authors gratefully acknowledge the Coordination for the Improvement of Higher Education Personnel (CAPES), Research Support Foundation of Rio Grande do Sul (FAPERGS) and National Counselor of Science and Technology (CNPq).

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