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Life Cycle Assessment Applied to Municipal Solid Waste Management: A Case Study

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Abstract

This study analyzes the environmental performance of the Municipal Solid Waste Management System (MSWMS) of Piedade, São Paulo, from a systemic perspective. A life cycle assessment (LCA) technique was applied according to an attributional approach to evaluate both the current operational situation and different prospective scenarios, which were devised based on the application of targets for recycling dry and wet waste suggested by the pre-draft version of the Brazilian Plan for Solid Waste. The life cycle impact assessment method EcoIndicator 99, in association with normalization and weighting procedures, was used to conduct the analysis. It was observed that the adoption of goals of 30%, 50% and 70% for recovering of the recyclable dry waste, resulted in improvement of the environmental performance of the waste management system under analysis, respectively of 10%, 15% and 20%. It was also possible to detect an evolution in the order of 54% in reducing impacts resulting from the adoption of targets for composting. LCA proved to be effective for the evaluation of the environmental performance of MSWMS-Piedade. However, for future evaluations, the attributional approach should be replaced by the methodological practice of substitution to enable the avoided burdens to be considered in estimations of the environmental performance municipal solid waste management systems.

Keywords: waste management system, landfill, environmental performance, life cycle assessment, public policies, sustainable development

Abbreviations

BPSW Brazilian Plan for Solid Waste

COTMAP Cooperative Workers of the Environment from Piedade

EIA Environmental Impact Assessment

FU Functional Unit

LCA Life Cycle Assessment

LCIA Life Cycle Impact Assessment

LCT Life Cycle Thinking

LWQ Index of Landfill Waste Quality

MBT Mechanical Biological Treatment

MSWMS Municipal Solid Waste Management Systems

NSIS National Sanitation Information System

SWM Index of Solid Waste Management

1. Introduction

With the approval and regulation of Law no. 12 305 of August 2, 2010 - BPSW, Brazil implemented a new legal framework for managing solid waste at the national level. Prevention and precaution, sustainable development, plans for solid waste, preparation of the inventory of waste, evaluation of product life cycles, and scientific and technological research were some of the issues established and regulated by this law (Brasil, 2011b).

According to Dias and Santos (2012), in considering urban solid waste, it is necessary to take into account spatial, environmental, health, social, cultural and institutional aspects. From the environmental perspective, the main challenges will be the definition of the best alternatives, which are not merely technological, to adopt to generate minor impacts. One way to solve the problem would be to use a combination of alternatives, i.e., the 3R approach of reuse, recycling and recovery, in all sectors of society. Another possibility would be to search for alternative treatments, destinations and methods for final waste disposal associated with the implementation of actions for reversing the logistics and effectiveness of selective collection (Dias & Santos, 2012).

Regarding the social aspects, Dias and Santos (2012) emphasize social inclusion as a key issue that must be addressed without paternalism as part of public policy under an institutional logic, effectively identifying the possibilities that a public policy can promote in terms of reducing inequalities and increasing social inclusion. Ferreira and Anjos (2009) noted that one of the populations subjected to exposure to municipal waste consists of the residents of the neighborhoods where treatment and disposal units of such waste are located. The better the technical standard is, the better the unit is in terms of its design, construction and operation. The issue of an offensive odor is always present when handling large amounts of household waste. This emission, the main factor for the closing of recycling and composting plants in Brazil, arises from the decomposition of organic matter.

An analysis conducted by the NSIS in 2011 showed that regular home collection of MSW reached 98.5% of the urban population of Brazilian municipalities. According to a statement by the municipal governing bodies that responded to the NSIS, the final disposition of the waste collected is distributed as follows: 74.9% to landfills, 22.8% to open dumps and 2.4% to sorting and composting units. The same survey also verified an increase in the occurrence of the practice of recovering recyclable waste around the country. During the period studied, this activity accounted for approximately one million tons of material, corresponding to 6.3% of the dry recyclable total (mostly paper, plastic, metal and glass) present in the collected mass (SNIS, 2013).

Additional parameters could be included in the analysis, such as gravimetric characterization of the waste, volumes of treated and reused waste, emissions from treatment units and final disposal, and fuel consumption and emissions associated with collection and transport (Paes, 2013). Moreover, the question could be treated with a systemic approach, a view that can be provided by LCT.

LCT considers the effect of environmental performance evaluation interactions that occur between a man-made system and its surroundings, which are necessary to meet certain demands. This framework therefore includes the lifecycle of a product, process or service. This lifecycle includes a set of actions that extends from the extraction of natural resources to the final disposition of the product or disabling of the process or service, passing through all chains of manufacturing, the actual use, and the reuse actions that are employed (Sonneman, 2002). LCT is based on LCA. Studies of this nature generate quantitative environmental diagnostics. Thus, among other uses, such studies are adequate to support the development of public policies (Coltro, 2007; Curran, 1996; UNEP, 2007).

According to McDougall, White, Franke, and Hindle (2001), an LCA study for performance evaluation of an integrated management system of solid waste is conclusive if its methodology can be extended to the EIA phase. At this level of advancement, environmental impacts associated with the consumption of resources and generation of waste from MSWMS not only diagnose the system performance but also serve as prospective trials of alternative approaches.

Pecora et al. (2012) compared hypothetical scenarios for the final disposal of urban waste for the city of São Paulo in terms of energy recovery through three technologies: landfills, incinerators and MBT. The authors concluded that landfills provided the worst results in terms of climate change, acidification, eutrophication, and photochemical ozone formation; the best performance was achieved by the incineration technology. However, the authors emphasized that the secondary treatment of the waste generated by incineration was not included in the study and that its inclusion would most likely change the results of the analysis.

The objective of this study is to evaluate the impacts and the environmental performance of the existing MSWMS in the city of Piedade (SP). Moreover, this study verified the environmental validity of prospective scenarios that consider the implementation of targets for the reuse of wet and dry waste suggested by the draft of the Brazilian

Plan for Solid Waste. As discussed later in the paper, these developments were carried out according to the methodological approach provided by LCA from an attributional perspective.

2. Methods

The methods applied to meet the objectives established for this study comprised the following steps: a) characterization of the current conditions of MSWMS in Piedade (SP); b) modeling of the system according to the consumption of resources and generation of waste; c) establishment of potential waste management scenarios – without selective collection and with recycling – defined from the guidelines and targets set out in the BPSW; d) application of the technique of LCA to each proposed scenario; e) evaluation of the environmental performance of each scenario, both from a global perspective (environmental impacts over the entire period) and from a temporal perspective (environmental impacts per year); and f) analysis of the results obtained and formulation of proposals for improving the efficiency of MSWMS in Piedade-SP.

2.1 Characterization of the System

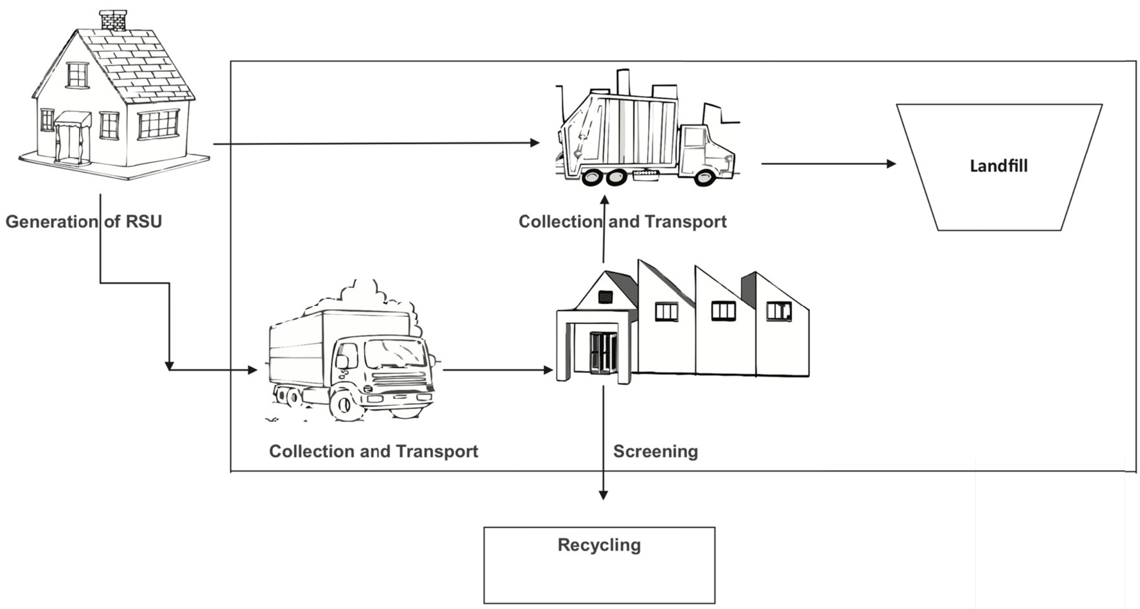

Figure 1. Flow diagram of functional elements of MSW management in the city of Piedade (SP)

Piedade is a municipality in the state of São Paulo located in the Metropolitan Region of Sorocaba (*23º42'43"S, 47º25'40" W*). The estimated population of Piedade in 2004 was 53 492, distributed over approximately 746 km^2 (IBGE, 2010).

In 2006, the local government implemented an MSWMS, which operates from a cooperative agreement established between this authority and the COTMAP. The MSWMS of Piedade comprises three stages: collection and transportation of solid waste and tailings, segregation of reusable materials, and final disposal of discarded materials in landfills.

The average generation rate of municipal solid waste in Piedade during 2011 was 42.2 t/d. According to the MSWMS guidelines, the collection of these materials can occur in two forms: common gathering and selective collection. In common gathering, the solid waste is collected without any prior separation by the generating sources – residential and commercial establishments and service – and sent directly to final disposal. For this process, there are two conventional trucks and four compactor trucks.

The selective collection of waste undergoes prior separation in households, from which the reusable material goes to the sorting center so that a more rigorous sorting can be performed. The materials classified as potentially reusable are distributed to recycling units, and the rejects are then disposed of in landfills. As selective collection involves smaller volumes of waste, the MSWMS has just one truck for this type of collection.

The segregation step is performed by COTMAP in a shed of approximately 750 m². The separation is conducted by an electric-powered press and burden lift. None of the sorting operations use thermal energy; however, some make use of electricity. In 2011, approximately 1.2 t/d of reusable materials was sold by COTMAP.

The MSWMS technological alternative for the final disposal of waste is a landfill with a surface area of 20 000 m^2. In operation since July 2006, this facility receives an average 41 t/d of waste generated by the city. At this rate, the closure of the facility was planned for mid-2013, after an expected lifetime of 7 years. The landfill was operated daily with a track tractor, backhoe and dump truck. Figure 1 presents a representation of the activities involved in the MSWMS in the city of Piedade.

Table 1 presents the daily average amounts and percentages for both recycled waste from selective collection and rejects that are sent for final disposal through ordinary collection (Brasil, 2011a). For leftovers from food and gardening – discharged in substantial quantities — there are no alternatives for reuse. Therefore, such materials are entirely converted to waste and taken to the landfill.

The item classified as ‘others’ comprises all material flows that do not fit into any of the other subdivisions. These materials include rubber and foam as well as products rarely encountered, such as electronic waste. Furthermore, items such as paper and metal, whose daily contributions account for approximately 610 kg and 400 kg, respectively, are considered to have the highest rate for reuse with selective collection services.

Table 1. Profiles of contributions per class of recycled waste and waste for final disposal

Class of solid waste	Recycled (%)	Landfilled (%)	Recycled (t/d)	Landfilled (t/d)
Organic leftovers from food and gardening	0.00	53.70	0.00	22.66
Paper and cardboard	1.44	7.70	0.61	3.27
Rags	0.00	6.10	0.00	2.57
Glass	0.14	1.73	0.059	0.73
Plastic	0.17	9.75	0.072	4.11
Metal	0.95	1.82	0.40	0.77
Aggregates	0.18	3.70	0.076	1.56
Others	0.00	12.56	0.00	5.30
Total	2.88	97.12	1.22	40.98

Source: Brasil (2011a).

2.2 LCA Modeling

This study was developed according to the conceptual framework provided by NBR ABNT ISO 14040 and 14044 standards, which describe general guidelines for attributional LCA (ABNT 2009a, 2009b). The objective of the LCA was to "*Manage the activities necessary for the Collection, Transport, Sorting and Final Disposal of Tailings and Urban Solid Waste from the City of Piedade-SP.*" Conceptually, the FU consists of the quantification of the function set for the LCA study (ABNT, 2009a). Therefore, the FU of this study was defined as follows: "*Manage the activities necessary for the Collection, Transport, Sorting and Final Disposal of 42.2 t/d of Tailings and Urban Solid Waste from the City of Piedade-SP.*"

The Product System refers to the set of anthropogenic interactions that will be evaluated by LCA. In this analysis, the Product System considered the steps outlined in the MSWMS of Piedade and the auxiliary elements that are also necessary for the performance of services undertaken by the MSWMS.

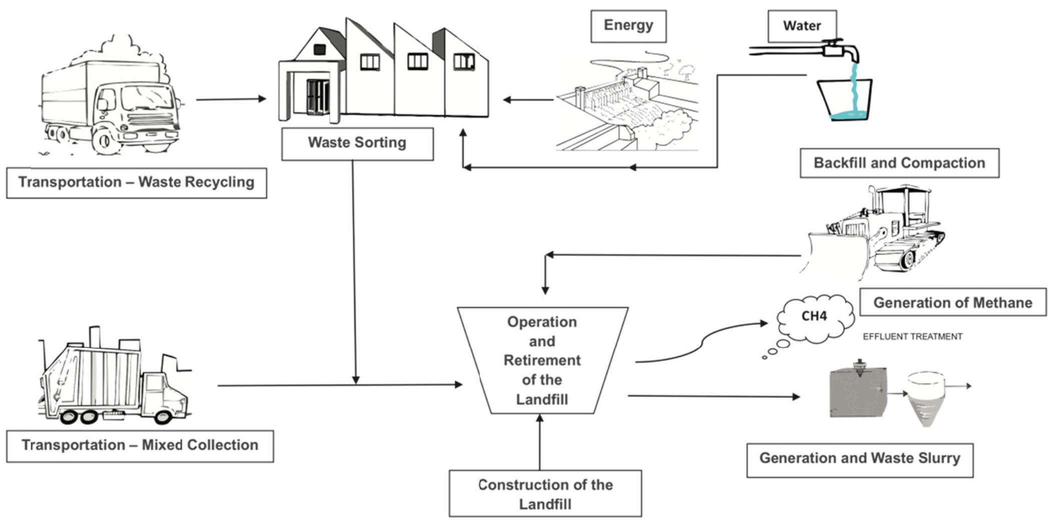

Figure 2. General approach of the Product System of the MSWMS-Piedade (SP)

As presented in Figure 2, the MSWMS included the operation of standard and selective waste and tailings collection, transport, waste sorting, and disposal of non-reusable materials in the landfill. Auxiliary operations included the generation and transport of electricity, water treatment, and production and consumption of diesel for transportation and machinery employed in the operation of the landfill.

Stages of construction and the maintenance of capital goods – machinery and modes of transport, routes of transport beyond the landfill itself – were also considered in the evaluation of environmental performance for this LCA study. The landfill was modeled and analyzed in terms of its construction, operation and decommissioning. The effluent from the leaching of solid waste by rainwater showed little significant contamination in measurement campaigns conducted regularly to monitor the landfill, indicating that it could be discharged to the receiving body without prior treatment.

The LCIA was conducted by the application of the method EcoIndicator 99 Midpoint (H) – version 2.09 (Goedkoop & Spriensma, 2012). This approach enabled the assessment of the environmental performance of MSWMS-Piedade for the following impact categories: Inhalation of Inorganic Compounds (IIC), Climate Change (CC), Ecotoxicity (ECT), Land Use (LAU), and Fossil Fuel Depletion (FF).

These impact categories were selected by considering the consumption and emissions of materials and energy that are associated with the MSWMS-Piedade. This action was taken to generate a more accurate diagnosis of the system functionality for different operating scenarios.

Another decision related to the LCIA was the application of the LCA procedures of normalization and weighting to the results obtained for all impact categories of LCIA. The use of these methodological practices can distort the final results of the analysis because these procedures expose the results to inaccuracies and even arbitrary processes. However, such effects are minimized because the assessment occurs by direct comparison of results. Moreover, these procedures allow for the establishment of single performance indicators for each scenario, which emphasize the collective effects, and enable the analysis to be conducted on an organizational level.

2.3 Characterization of the Prospective Scenarios

Alternative proposals for prospective assessments of performance for MSWMS were established for different recycling rates, which are based on guidelines and pre-outlined targets in the BPSW. This approach highlights the reduction of dry municipal solid waste disposed of in landfills, the inclusion of waste pickers of reusable and recyclable materials, the reduction of wet municipal solid waste disposed of in landfills, and the treatment and recovery of landfill gases (Brasil, 2011b). Based on these guidelines, the BPSW sets targets for the reduction of dry and wet waste disposed of in landfills. For dry waste, the document establishes favorable, intermediate and unfavorable targets for the recycling of dry waste at 70%, 50% and 30%, respectively. For wet waste, this study considered only the intermediate target of a 37% reduction in wet waste disposed of in landfills (Brasil, 2011b).

Based on this approach, six possible scenarios for the operation of MSWMS-Piedade were developed. Scenario S1 considered that there was no selective collection activity. Therefore, all 42.2 t/d of solid waste would be landfilled.

S2 considered the current operational reality of the system in which 41 t/d of MSW is disposed of in the landfill and the remaining 1.2 t/d of recyclable materials goes to the segregation center to be marketed to recycling companies.

Scenarios S3, S4 and S5 adopted targets for the reuse of dry waste at 30%, 50% and 70%, respectively. Therefore, S3 considered a landfill amount of 37.89 t/d MSW and sent the remaining 4.31 t/d of dry waste to the recycling center. For S4, the ratio was 35.75:6.45, and in the case of S5, the ratio was 33.66:8.54.

Scenario S6 implemented the target of 37% reduction of urban wet solid waste disposed of in landfills and 30% recycling of dry waste. These adjustments resulted in a daily rate of solid waste disposal of 18.57 t, with the remaining 23.63 t forwarded for recycling.

Table 2 describes the quantities intended for landfilling and reuse that were set for each scenario. The table also lists the targets set out in the draft BPSW and the percentages of reuse. The effective rates of reuse express the amount of waste that is not taken to the landfill because the BPSW targets were multiplied by the amounts of waste presented in Table 1.

The highest rates of waste recycling occur in situations in which actions are taken on the wet waste – food and garden scraps – because of its substantial contribution to the total amount generated and because MSWMS does not predict the reuse of these waste materials in its original version (Table 1). This situation is examined in terms of environmental performance under Scenario S6.

Table 2. Amounts of disposal in landfill and reuse rates from the guidelines defined in BPSW

Scenario	Landfill (t)	Selective Collection (t)	BPSW target Dry Waste (%)	BPSW Target Wet Waste (%)	Landfill (%)	Utilization Index (%)
S1	42.20	0.00	0.00	0.00	100.00	0.00
S2	41.00	1.20	0.00	0.00	97.16	2.84
S3	37.89	4.31	30.00	0.00	89.79	10.21
S4	35.75	6.45	50.00	0.00	84.72	15.28
S5	33.66	8.60	70.00	0.00	79.76	20.24
S6	18.57	23.63	30.00	37.00	44.00	56.00

3. Results and Discussion

Table 3 presents the environmental performance of Scenarios S1 to S6 for the impact categories under analysis. The similarity of performance among the scenarios for all impact categories stands out in a preliminary analysis. The exception occurred for the impacts of CC in S6, which were approximately 30% higher than those of the other alternatives. Therefore, the global environmental performance of SMWSM-Piedade would not be affected by applying the targets of 30%, 50% and 70% for recycling dry waste defined in BPSW. This finding might be explained by three factors. The first factor involves the minimally significant contribution of these materials in comparison to those from organic waste – food and gardening materials – which are the main contributors in terms of solid waste generation in the municipality (Table 1).

The second factor is related to the energy consumption associated with the classification of the dry waste process. This energy consumption is high because the equipment that performs this function – compressing and lifting of the materials – would operate at overcapacity due to the increase in material to be treated in the segregation unit.

The third factor involves the potential benefits for environmental performance that could be generated by the increase in the lifetime of the landfill – provided by successive increases in the rate of reuse of dry material – which were not very significant. However, this effect may have been dampened due to the application of LCA according to a purely attributional approach and, hence, without considering the effects of avoided burdens.

A discretization of data from Table 3 indicates that the performance of MSWMS-Piedade is mainly influenced by the impact category of fossil fuel reduction, whose contribution to all scenarios was at a level of 12.8 Pt. For S1 to S5, this amount corresponded to approximately 59% of the total impact, whereas in S6, this contribution comprised 56.4%.

Table 3. Comparison of environmental performance among scenarios

Impact Category	Unit	S1	S2	S3	S4	S5	S6
IIC	Pt	4.31	4.31	4.31	4.31	4.31	4.32
CC	Pt	3.64	3.62	3.64	3.65	3.68	4.81
ECT	Pt	0.22	0.22	0.22	0.22	0.22	0.23
LAU	Pt	0.57	0.57	0.57	0.58	0.58	0.58
FF	Pt	12.82	12.82	12.82	12.82	12.83	12.85
Total	Pt	21.56	21.54	21.56	21.58	21.62	22.79

The constancy of the values for FF, as well as those that describe the environmental performance of the system in terms of inhalation of inorganic compounds (IIC), stems from the same source: the transport operations relating to the collection and distribution of waste. What stands out in this case is not only that the trucks used in these actions are obsolete and require constant maintenance but that the daily distances traveled to the landfill or the recycling plant are equivalent because these units are adjacent to one another.

Impacts regarding CC are basically due to emissions from CO_2 and CH_4 from transport and the generation of CH_4 in the landfill. Regarding the latter source, the extension of the landfill operational lifetime is a determining factor.

Combining data from Tables 3 and 4 reveals that the gradual expansion of the lifetime of the landfill from 7 years (S2) to 8.53 years (S5) does not provide a significant intensification of impacts to CC. However, when the time horizon reaches 15.45 years (S6), an increase –discussed above – of approximately 30% (4.81 Pt) is achieved.

Finally, the environmental effects caused by MSWMS-Piedade in terms of Ecotoxicity (ECT) and land use (LAU) were both stable and minimally significant. The ECT results derive from the slight contamination of the leachate from the landfill.

Table 4. Increase in global environmental impacts compared with Scenario S2 and operating time of MSWMS

Scenario	Total Environmental Impacts (Pt)	Operating Time (yrs.)
S1	22.45	6.80
S2	22.42	7.01
S3	22.45	7.57
S4	22.47	8.03
S5	22.50	8.53
S6	23.70	15.45

The performance of LAU can be justified due to the environmental burdens associated with the construction of the enterprise, which exercise little influence on the final result of the analysis in comparison to the effects of the operation, regardless of the scenario that is being analyzed. Once again, it is important to note that an application of the technique of LCA under the substitution approach (i.e., avoided burden) would lead to different conclusions.

The way the environmental performance results, shown in Table 3, might suggest that the partial recycling of wet and dry waste worsens the environmental performance of MSWMS-Piedade. To verify and better explain such a conclusion – which is dissonant with common sense with respect to these practices – a complementary analysis was carried out. In this analysis, a measurement of the environmental performance of each alternative analysis was conducted, taking into account the temporal perspective. Therefore, a relationship of overall environmental impacts with the operating time was established for each scenario in order to rectify the negative effects that were apparently caused by recycling.

The environmental performance of each scenario was expressed according to the Specific Performance Index (SPI), an indicator that relates the cumulative environmental performance with the total operating time of the system for each situation (Table 4). Regarding the units, SPI is quantified as '*Pt /yr.*' The SPI values for Scenarios S2 to S6 were individually compared with the results obtained for S1 – $(SPI)_{S1}$ – , defined as the baseline scenario because it does not involve any recycling action in the operation of MSWMS. This procedure makes possible to calculate another index, Environmental Relative Performance (ERP), obtained from the expression (Equation 1):

$$ERPi = [1 - ((SPI)_i / (SPI)_{S1})] \times 100\% \quad (1)$$

ERP_i = Environmental Relative Performance for a specific scenario (%)

SPIi = Specific Performance Index for Scenarios S2 to S6 (Pt/yr.)

$(SPI)_{S1}$ = Specific Performance Index for Scenario S1 (baseline) (Pt/yr.)

Table 5. Values of Reutilization Index, SPIi and ERPi per scenario

Scenario	Recycling Index (%)	SPI_i (Pt / Yr.)	ERP_i (%)
S1	0.00	3.30	–
S2	2.84	3.20	3.03%
S3	10.21	2.97	10.0%
S4	15.28	2.80	15.1%
S5	20.24	2.64	20.0%
S6	56.00	1.53	53.6%

Table 5 associates values of SPI_i and ERP_i with the Recycling Index, which correlates the daily amounts of material absorbed by the selective collection program with the total solid waste generated by the municipality (Table 2)

An analysis of the values indicates that successive improvements in SPI with respect to the baseline situation occur with an increased recycling rate. These advances result in positive values of ERP, from which it is possible to conclude that adopting recycling practices provides a reduction in the environmental impacts of the annual system. Moreover, from the implementation of actions and targets for the recovery of wet wastes, is it possible to obtain an annual reduction in environmental impacts of approximately 54%.

4. Conclusions

This study evaluated the environmental performance of the MSWMS of the municipality of Piedade (SP) for different operational scenarios, which were created based on guidelines and targets set out in the BPSW. The life cycle impact assessment method of EcoIndicator 99 – Midpoint (H) with the application of the methodological procedures of normalization and weighting was used to conduct the analysis. In a preliminary assessment, the results indicated similarity in performance among the scenarios, suggesting that the targets for recycling established by BPSW did not affect the environmental performance of the system. However, a detailed analysis in which the same performances were verified under a temporal perspective concluded that the adoption of recycling practices provides successive reductions in environmental impacts, which directly vary with the lifetime of the system.

The most relevant environmental impact associated with the operation of the system occurs in terms of fossil fuel depletion. Values for the normalized performance of this effect ranged from 56.4% to 59% of the total impact for the scenarios studied. Impacts related to climate change are due to emissions of CO_2 and CH_4 from transport and CH_4 emissions in the landfill. Effects regarding Ecotoxicity and Land Use were stable and of little importance.

It was observed that the adoption of goals of 30%, 50% and 70% for recycling of dry waste, suggested by the pre-draft version of the National Plan for Solid Waste, resulted in improvement of the environmental performance of the waste management system under analysis, respectively of 10%, 15% and 20%. It was also possible to detect an evolution in the order of 54% in reducing impacts resulting from the adoption of targets for composting.

Even through the boundaries of the system adopted, it is interesting to note how the recycling of wet and dry waste can reduce the annual environmental impacts of all MSWMS of the city; apart from generating other benefits like increasing the operating time of the landfill from the current 7 years (Scenario 2) to 15.45 years (Scenario 6). Thus the method used for assessing impacts was sensitive to introduction of recycling of wet and dry waste, such as management strategy, and that could double the useful life time of the landfill.

LCA proved to be an effective tool for evaluating the performance of MSWMS-Piedade. The results of this analysis provided data and information necessary for a decision-making process in which the environmental perspective can be taken into account. However, for future evaluations, the attributional approach should be replaced by the methodological practice of substitution to enable the avoided burdens arising from features of the system to be considered in the estimation of the environmental performance of municipal waste disposal systems.

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