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Steps towards more environmentally sustainable municipal solid waste management – A life cycle assessment study of São Paulo, Brazil

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ABSTRACT

Landfill disposal has thus far been the predominant treatment method for municipal solid waste (MSW) throughout Brazil, including São Paulo city. Environmentally sustainable development of MSW management in São Paulo necessitates a stepwise reduction of landfilling. However, ever increasing MSW generation poses the challenge of managing increasing MSW volumes while simultaneously modernizing the MSW management system. In this study, the environmental impacts of the current MSW management system and future alternatives in the city were assessed by means of life cycle assessment (LCA) to determine a pathway towards more environmentally sustainable MSW management. The assessed impact categories were global warming, acidification and eutrophication potentials. Potential future alternatives included the stepwise reduction of landfilling by the introduction of composting, anaerobic digestion and mechanical-biological treatment (MBT). The results of the study indicated that the environmental impacts of MSW management in São Paulo can be most effectively diminished by anaerobic digestion of source separated organic waste and MBT of MSW, on condition that the produced refuse-derived fuel (RDF) is utilized in cement production as a substitute for coal. The other utilization option for RDF, incineration, would increase the environmental impacts of MSW management due to the low amount of avoided emissions resulting from electricity substitution since average electricity production in Brazil is dominated by hydropower. Sensitivity analyses indicated, however, that the environmental impacts of incineration might decrease with different modeling assumptions, e.g. the modeling assumption regarding the kind of electricity production substituted by electricity production from MSW. Nevertheless, the main findings of the study remained the same and they are in line with the previous literature.

1. Introduction

Ever greater generation of municipal solid waste (MSW) is becoming an increasingly pressing issue globally, particularly in emerging economies and developing countries, where the local infrastructure and MSW management systems cannot always keep up with the larger MSW volumes resulting from rapid population and economic growth as well as increased urbanization (Guerrero et al., 2013). The World Bank (2012) has forecast that global MSW generation will double by 2025 (2012 as a reference year). Emerging economies, in particular, China, India and Brazil, will play a crucial role in addressing this global issue. In volume, China is the world's largest generator of MSW, and India and Brazil are third and fourth largest, respectively (Waste Atlas, 2017).

Brazil generates approximately 63 million tonnes of MSW annually (Waste Atlas, 2017). Annual MSW generation per capita is approximately 380 kg, which is lower than typically found in upper middle income countries (approximately 440 kg according to World Bank (2012)). Taking into account the strong correlation between MSW generation and income level, MSW generation per capita can be expected to increase over the following years, should Brazil, as forecast, recover from the current recession (World Bank, 2017a). Despite uncertainty surrounding the economic prospects of the country, total MSW generation will however continue to increase due to population growth (World Bank, 2012). Statistics for the national economy for 2013 to 2016 show that while gross national income (GNI) per capita decreased by 30.6%, the total population increased by 2.6%. Although population growth has

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decelerated slightly, due to the poor economic situation, the growth curve has nevertheless remained positive (World Bank, 2017b). Brazil will thus face the tough challenge of managing increasing MSW generation while simultaneously developing its MSW management systems in a more sustainable direction.

São Paulo is the most populous city in Brazil and the case area of this study (see Fig. 1). The city is the capital of São Paulo state, which is the world's largest MSW generator at a regional level, generating approximately 20 million tonnes of MSW annually, of which 4.7 million tonnes are generated in São Paulo city (CCAC, 2015a; Waste Atlas, 2017). It has been estimated that 97.8% of MSW generated in São Paulo is under the formal MSW management system. In addition to the formal MSW management system, individual pickers and picker organizations collect recyclables informally. Formally collected MSW is disposed of in the city's two sanitary landfills (i.e. landfills with landfill gas (LFG) and leachate collection systems). In addition, São Paulo has two mechanical sorting plants for separately collected recyclables such as plastic, paper, cardboard, metal and glass. Formally collected recyclables constitute, however, only a minor proportion of total MSW generated (approximately 1%, 50 000 tonnes/a) (CCAC, 2015a; CCAC, 2015b).

The future strategy for MSW management in São Paulo is described in PGIRS (Plano de Gestão Integrada de Residuous Solidos), the MSW management plan of the city, launched in 2014 (Prefeitura de São Paulo, 2014). One of the main priorities of PGIRS is reduction of the volume of MSW disposed of in landfills. Organic waste management can play an important role in achieving this objective, since approximately half of MSW is organic waste. Consequently, source separation and separate treatment of organic waste would efficiently reduce the volume of MSW landfilled, and thus the environmental impacts. Both composting (including home composting) and anaerobic digestion (AD) are proposed in PGIRS as potential treatment methods for organic waste. Some small-scale initiatives promoting home composting already exist (Composta São Paulo, 2017) but no composting or AD plants are currently operational in São Paulo, based on information from 2016, when the data for this study was collected. In addition to the abovementioned treatment methods, mechanical-biological treatment (MBT) is proposed in PGIRS as a potential treatment method (CCAC, 2015a; Prefeitura de São Paulo, 2014).

São Paulo city
- Population: 11-12 million, depending on the source
- Surface area: ~1500 km^2
- MSW generation: ~400 kg/capita/year

Fig. 1. Background information about São Paulo.

Life cycle assessment (LCA) is a method for estimating the potential environmental impacts of products or systems (EN ISO 14040, 2006; EN ISO 14044, 2006). LCA has been utilized in the field of MSW management since the 1990s, and it is currently a widely used technique to assess the environmental impacts of MSW management systems (Laurent et al., 2014). LCA enables comparison of different MSW management strategies and treatment methods in terms of their environmental impacts, which makes it a useful tool for decision- and policy-making (e.g. Karmperis et al., 2013; Turner et al., 2016).

A vast number of studies have been published that investigate different aspects of MSW management in different parts of the world – and Brazil is no exception. For example, the electricity production potential of MSW in Brazil was the focus of Leme et al. (2014), Lino and Ismail (2011) and Mambeli Barros et al. (2014). LCA studies focusing on comparison of alternative MSW treatment methods in a given case area are also common. For instance, Goulart Coelho and Lange (2016) and Bernstad Saraiva et al. (2017) recently assessed the environmental impacts of MSW management alternatives in Rio de Janeiro by means of LCA. LCA studies of MSW management in São Paulo, the case area of this study, have also been published. Mendes et al. (2003) assessed the environmental impacts (namely global warming, acidification and nutrient enrichment) of organic waste treatment in São Paulo using LCA. They compared three different treatment methods for organic waste: landfilling, composting and AD. Both composting and AD had lower environmental impacts than landfilling, with one exception: composting had the highest acidification potential of the three treatment methods. AD had lower environmental impacts than composting (conventional composting without biofiltration).

In another study, i.e. Mendes et al. (2004), the same authors used LCA to compare the environmental impacts (for the same impact categories as above) of landfilling and MSW incineration for São Paulo. It was found that landfilling had higher environmental impacts than incineration. However, the differences were not great due to the structure of the electricity production sector in Brazil, where a vast majority of electricity is produced by hydropower (94% in Mendes et al. (2004)). Therefore, electricity production from MSW did not yield a significant amount of avoided emissions. More recently, Soares and Martins (2017) conducted a gate-to-grave LCA for 1 tonne of MSW received in CTVA Caieiras landfill, one of the sanitary landfills in São Paulo. In the study, the environmental impacts of various waste-to-energy options - LFG combustion with energy recovery, MBT combined with AD, and incineration – were evaluated. It was found that MBT combined with AD had the lowest environmental impacts of the scenarios assessed in the study. Being a site-specific gate-to-grave LCA, the study did not cover the entire life cycle of MSW, i.e. from MSW generation to its final treatment or disposal. As evident from the above examples, previous LCA studies of the MSW management system of São Paulo have focused more on specific treatment methods and their environmental impacts, rather than assessing comprehensively the environmental impacts of the MSW management system as a whole consisting of different treatment options and methods for different MSW flows (e.g. organic and residual fraction of MSW).

This study uses LCA to assess the environmental impacts of different management alternatives for MSW in São Paulo in order to determine a pathway towards more environmentally sustainable MSW management in the city. The study takes into account the entire life cycle of MSW: from MSW generation to its final treatment or disposal. Both organic and residual fractions of MSW are assessed in the study. The scenarios the study are based on the development proposals and objectives of PGIRS, and they present potential improvement steps for the system. The research questions of the study are the following:

- What are the environmental impacts of MSW management in São Paulo?
- In which direction should the system be developed in order to diminish the environmental impacts of MSW management in the city?

2. Materials and methods

2.1. MSW management in São Paulo

Household waste, street cleaning waste as well as waste from markets and commercial activities generating less than 50 kg per day are regarded as MSW in São Paulo. Total MSW generation in São Paulo is approximately 4.7 million tonnes/a (CCAC, 2015a). The vast majority of MSW in São Paulo is mixed MSW from households; in 2015, 3.8 million tonnes of mixed MSW was collected and treated (AMLURB, 2016). Mixed MSW refers to the remaining part of MSW after the source separation of recyclables. This study focuses on this particular MSW flow, i.e. formally collected and treated mixed MSW from households, since formal information is available and such waste constitutes the majority of total MSW generated (henceforth in this study MSW refers solely to mixed MSW from households due to above-mentioned reasons). Formally collected and treated recyclables are not taken into account in the study since they compose only a minor proportion of the total MSW generation, and they are already treated in an environmentally sustainable manner, on the presumption that the collected materials are truly reclaimed. Informally collected recyclables are not assessed in the study since no formal information was available.

The MSW management authority of São Paulo, AMLURB, has contracted out MSW management activities to two private companies: Loga and Ecourbis (CCAC, 2015a). The division between the companies is geographical. Loga is responsible for management of MSW generated in the northern and western parts of São Paulo, whereas Ecourbis is in charge of the MSW generated in the southern and eastern of the city (AMLURB, 2016). There are two landfills in São Paulo: the Central de Tratamento Leste (CTL) landfill (Ecourbis) and the Central de Tratamento e Valorização Ambiental (CTVA) Caieiras landfill (Loga). MSW is transported either directly or via transfer stations to the landfills. There are three transfer stations in the city; Ecourbis owns and operates two of them (Santo Amaro and Vergueiro), and Loga one (Ponte Pequena). Both companies have their own collection and transportation fleets. There are two mechanical sorting plants in the city. However, only a minor proportion of MSW is treated in these plants, and the vast majority of MSW is disposed of in landfills, as mentioned earlier (CCAC, 2015a). Different MSW streams and the average composition of mixed MSW in São Paulo are presented in Fig. 2. As can be seen, organic waste predominates, forming 49% of the composition of mixed MSW.

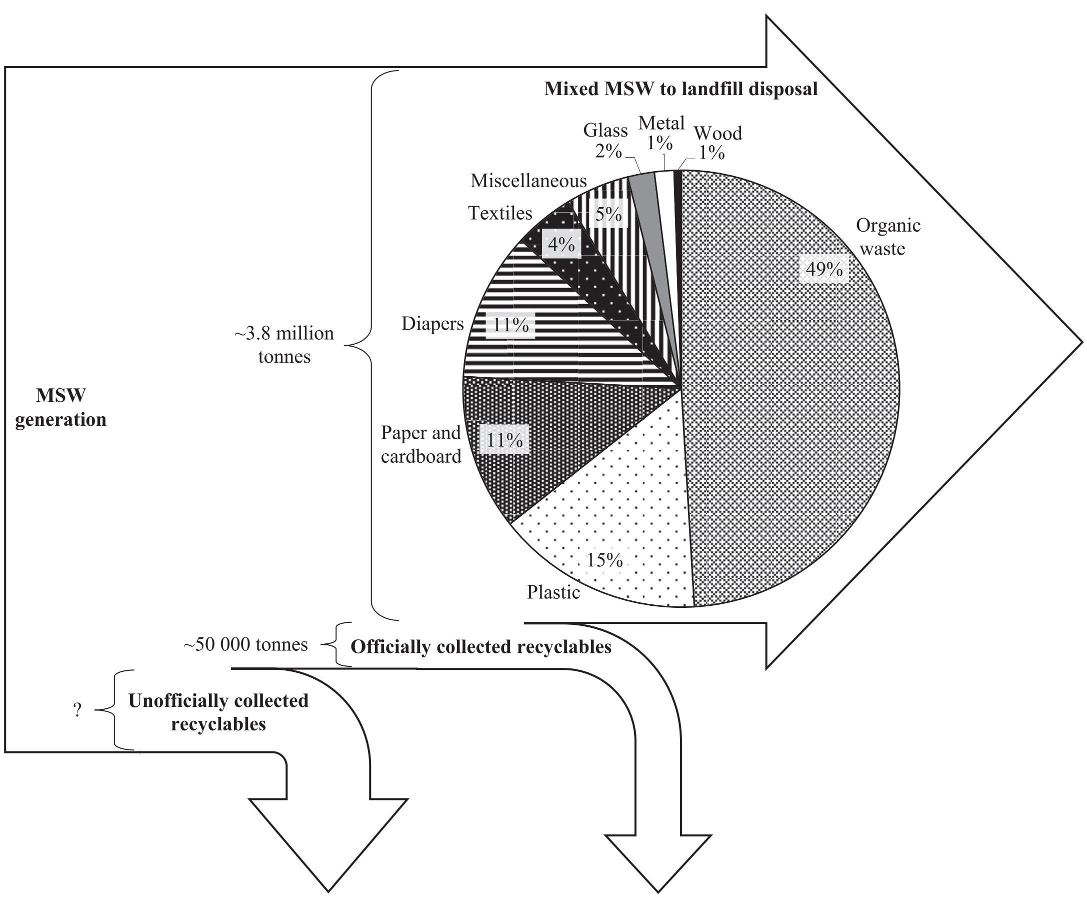


Fig. 2. Different MSW streams and the composition of mixed MSW in São Paulo (AMLURB, 2016; CCAC, 2015b).

2.2. Life cycle assessment

The LCA was conducted in accordance with the ISO standards 14040 (2006) and 14044 (2006). The impact categories assessed in the study were global warming potential (GWP) for a 100 year time span, acidification potential (AP) and eutrophication potential (EP), since the required life cycle inventory (LCI) data was available (see Section 2.2.2 and Supplementary material A-D for further information about the LCI data). Sufficiently comprehensive LCI data about other possibly relevant impact categories (e.g. human toxicity potential) was not available, and they were therefore excluded from the study. The modeling for the study was done with GaBi LCA modeling software (version 7) (Thinkstep, 2017), and the CML 2001 (April 2015) was used for impact assessment. The functional unit is the treatment of formally collected mixed MSW in São Paulo in one year. 2015 was selected as the reference year: 3.8 million tonnes of MSW were formally collected and treated in that year (AMLURB, 2016). The study takes into account the entire life cycle of MSW in São Paulo, i.e. generation, collection, treatment and the final disposal of waste. The relevant unit processes regarding the different life cycle phases are included in the system boundaries of the study (see Section 2.2.2 for further information). The study has a consequential approach, i.e. in addition to the direct emissions resulting from the unit processes, the study takes into account avoided emissions resulting from energy and material substitution (i.e. energy recovery from MSW and recycling). The context situation of the study was considered as a micro-level decision support, i.e. the study was assumed to have no large-scale consequences on the background system (e.g. the national electricity production market) (EC-JRC, 2010). Therefore, the produced electricity from MSW was assumed to substitute average electricity production in Brazil. Hydro (75.2%), natural gas (8.5%), biomass (6.3%), heavy fuel oil (3.5%) and nuclear (2.9%) are the main energy sources for electricity production in Brazil (Thinkstep, 2016).

2.2.1. Scenarios

The scenarios considered in the study represent potential treatment methods for MSW in São Paulo and are stepwise improvements towards a more environmentally sustainable MSW management system in the city. The strategic MSW management development plans of the city are taken into account in the scenarios: the treatment methods employed in the scenarios are proposed in PGIRS as potential treatment methods for MSW in São Paulo – composting, AD and MBT.

There are five main scenarios in the study (Scenarios 0–4). Additionally, there are sub-scenarios in Scenarios 2, 3 and 4. The sub-scenarios indicate the treatment method for separately collected organic waste: composting (X.1) or anaerobic digestion (X.2). In the baseline scenario (Scenario 0), which is the status quo, 100% of collected MSW is disposed of in landfills. Scenario 1 is a combination of home composting and landfilling: 5% of organic waste (i.e. 2.5% of the total MSW) is home composted and the residual MSW (i.e. the remaining MSW after the separation of organic waste) is disposed of in landfills. A 5% home composting rate was chosen since the objective regarding home composting in PGIRS is highly ambitious: 33% home composting rate of organic waste by 2033 (Prefeitura de São Paulo, 2014). However, in a shorter time span the objective is not realistic since approximately 5% of organic waste is composted in Brazil at present (CCAC, 2015a). Therefore, we employed a more realistic rate for home composting in the study.

In Scenario 2, the home composting of organic waste is accompanied by the separate collection and treatment of organic waste: 20% of organic waste (i.e. 9.8% of the total MSW) is either composted (Scenario 2.1) or anaerobically digested (Scenario 2.2) and the residual MSW is landfilled. We selected a 20% separate collection rate based on the PGIRS strategy objective of establishing new organic waste treatment facilities. The aim is that the total treatment capacity of the facilities would be 19% of total MSW generation, and 40% of organic waste generation by 2023 (CCAC, 2015a). In view of the current situation, no operating composting or AD plants, a more realistic mid-term goal of a 20% separate collection and treatment rate for organic waste was employed in the study.

In Scenarios 3 and 4, MBT of the residual MSW is included in the assessment: 20% of the residual MSW (i.e. 17.6% of the total MSW) is treated in MBT plants, while the rest of the MSW is disposed of in landfills. PGIRS contains no specific objectives regarding the MBT of MSW. Therefore, a realistic mid-term MBT capacity was employed, as with the organic waste treatment plants. Scenarios 3 and 4 differ in the utilization of the refuse-derived fuel (RDF) produced. The RDF is incinerated in waste-to-energy plants in Scenario 3, whereas in Scenario 4, it is utilized in cement production as a substitute for coal, which is typically used as the primary fuel in cement kilns. The treatment method for the generated organic reject is either composting or AD, depending on the sub-scenario (Scenarios 3.1 and 4.1 → composting; Scenarios 3.2 and 4.2 → AD). The scenarios are hierarchical (see Fig. 3), i.e. the improvement steps taken in previous scenarios are also included in the following scenarios. The MSW mass flows of the scenarios are presented in Table 1.

2.2.2. System boundaries and calculation principles

The system boundaries of the study (see Fig. 4) include direct emissions from transportation and treatment of MSW (including electricity and diesel consumption) as well as avoided emissions resulting from material and energy substitution. The entire MSW management system of São Paulo was assessed in the study, i.e. the study takes into account the MSW management operations of both Ecourbis and Loga.

São Paulo city has 32 districts, of which 19 are in the operation area of Ecourbis and 13 in the operation area of Loga (AMLURB, 2016). The collection and transportation of MSW was modeled for each district individually (see supplementary material A). The calculation principles for transportation distances are presented in Fig. 5. The following assumptions were made. The payload capacity of a truck was either 11 or 25 tonnes depending on whether MSW was directly transported to a MSW management site or via a transfer station. Trucks carried a full payload to a MSW treatment site and returned back empty. Organic waste was directly transported to a MSW treatment site due its high moisture content. All MSW treatment plants (i.e. composting, AD and MBT plants) were assumed to be located at the current landfill sites, CTL and CTVA Caieiras. Using the above-mentioned assumptions, the emissions from transportation were calculated with the GaBi software (i.e. the unit emissions of trucks were derived from GaBi's database).

Landfilling of the MSW was modeled mainly based on information received during visits to the CTL and CTVA Caieiras landfills (site-specific data). The modeling was complemented with literature data if necessary. The methane (CH_4) generation potential (L_0) of MSW is one of the most critical parameters in terms of the environmental impacts of landfilling, particularly GWP (Liikanen et al., 2017). CH_4 generation potential was calculated using the following equation:

$$L_0 = DOC \times DOC_f \times MCF \times F \times \frac{16}{12} \quad (1)$$

where $L_0 = CH_4$ generation potential [Gg_{CH4}/Gg_{MSW}]

$DOC =$ Fraction of degradable organic carbon [Gg_C/Gg_{MSW}]

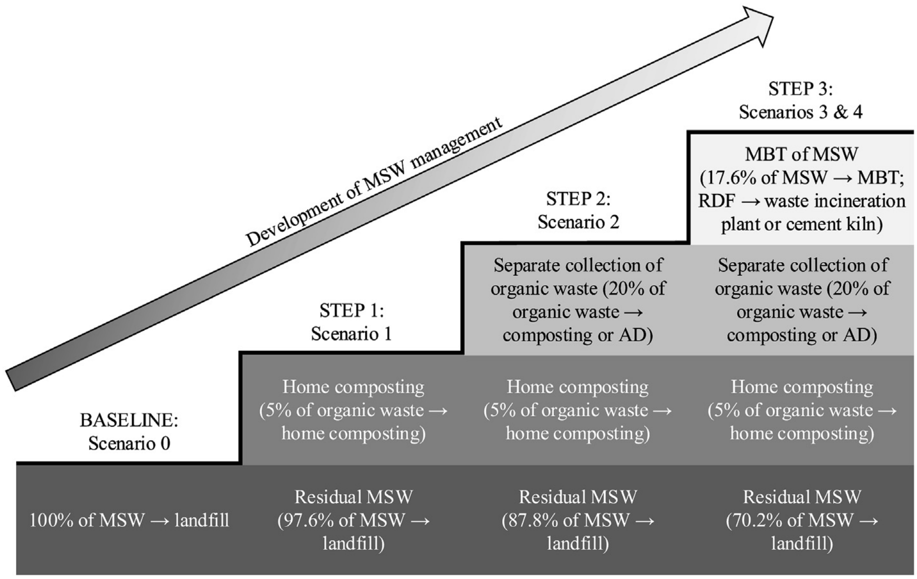


Fig. 3. Scenarios of the study.

Table 1
Mass flows of MSW in the scenarios.

Scenario	Landfill [kt]	Treatment of organic waste [kt]			MBT [kt]		∑
		Home composting	Composting plant	AD	Incineration	Cement kiln	
0	3800	–	–	–	–	–	3800
1	3707	93	–	–	–	–	3800
2.1	3335	93	372	–	–	–	3800
2.2	3335	93	–	372	–	–	3800
3.1	2668	93	372	–	667	–	3800
3.2	2668	93	–	372	667	–	3800
4.1	2668	93	372	–	–	667	3800
4.2	2668	93	–	372	–	667	3800

DOC_f = Decomposable fraction of DOC [%]
MCF = CH_4 correction fraction [-]
F = Share of CH_4 in landfill gas (LFG) [%]
16/12 = The molecular weight ratio between CH_4 and C [-] (IPCC, 2006).

L_0 is the total amount of CH_4 generated in the decomposition of MSW. Since CH_4 generation continues for decades after the disposal of MSW (IPCC, 2006), L_0 was employed in modeling in order to take into account the entire life cycle of MSW. Data used in the modeling of landfilling, including the above-described L_0, is presented in supplementary material B.

The home composting of organic waste was modeled based on literature data (Andersen et al., 2012; Boldrin et al., 2009). It was assumed that the generated compost substituted multinutrient fertilizers in domestic use. The substituted multinutrient fertilizer was a NPK fertilizer containing nitrogen, phosphorus and potassium at the same proportion (each 15% of the total content). Data used to model the environmental impacts of home composting is presented in supplementary material C.

Since there were no operational composting or AD plants in São Paulo in 2016, when the data for the study was collected, both treatment processes were modeled based on literature data. The studies of Boldrin et al. (2009), Brown et al. (2008) and Pagans et al. (2006) were utilized in modeling of the composting process (see supplementary material C for further information). Windrow composting was assumed for the composting technology. It was considered as a potential composting technology in the case area since it is a rather simple and consequently low-cost composting technology, and it has been applied in Brazil (Santos et al., 2017). The generated compost was assumed to substitute similar multinutrient fertilizer as in the home composting process. The AD process was modeled based on the studies of Angelidaki et al. (2006), Berglund and Börjesson (2006), Havukainen et al. (2017), Møller et al. (2002) and Nielsen et al. (2010) (see supplementary material C for further information). The generated digestate was assumed to be windrow composted. As in the composting process, the generated compost from pile composting was assumed to substitute conventional NPK fertilizer.

MBT of the MSW was also modeled based on literature data due to a lack of site-specific data - there were no operating MBT plants in São Paulo in 2016. The studies of Damgaard et al. (2009), Leme et al. (2014) and Nasrullah et al. (2015) were employed in the modeling of MBT (see supplementary material D for further information). Compost generated from mechanically separated organic reject (approximately 28% of input MSW) was assumed to be used as a landfill cover material instead of fertilizer due to the lower compost quality. Mechanically separated organic reject contains more harmful substances (e.g. heavy metals) and other unwanted materials (e.g. plastic) than source separated organic waste (Di Lonardo et al., 2012), which may restrict the utilization of compost in fertilizing, soil improvement and landscaping purposes. The treatment of organic reject (i.e. composting or AD) was

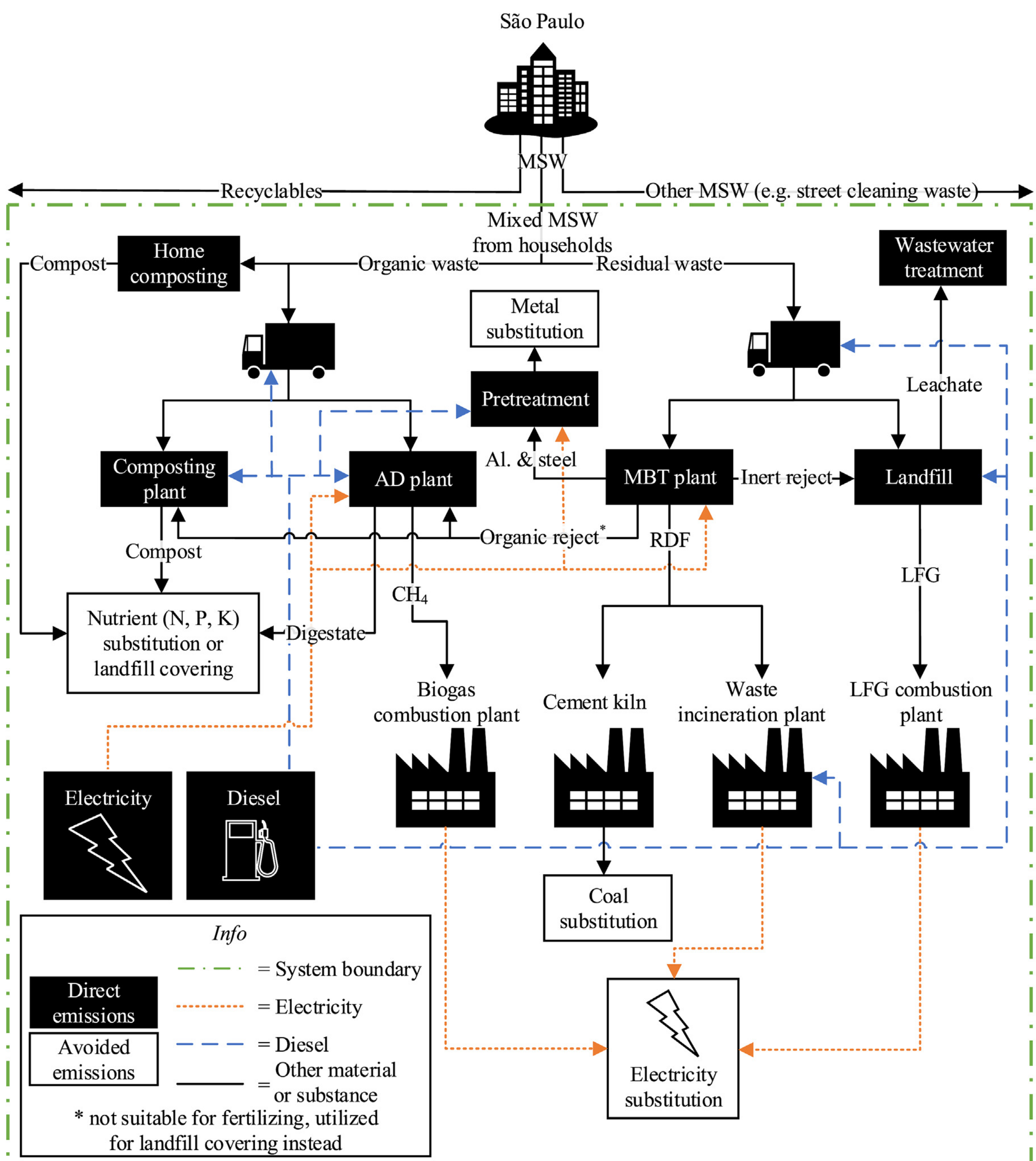


Fig. 4. System boundaries of the study.

otherwise modeled similarly as described above.

Incineration of the RDF was modeled based on the studies of Astrup et al. (2009), Birgisdóttir et al. (2006), Consonni et al. (2005), Havukainen et al. (2017), Hupponen et al. (2015), Leme et al. (2014) and Mendes et al. (2004) (see supplementary material D for further information). The utilization of RDF in cement production as a substitute fuel for coal was calculated based on the energy content (lower heating value, LHV) of RDF. Avoided acquisition (i.e. mining, processing and transportation) and combustion of hard coal in cement production were taken into account in the study, whereas other emissions from cement production were excluded from the assessment.

3. Results and discussion

3.1. Contribution analysis

In contribution analysis, the total result is decomposed into individual process contributions (Clavreul et al., 2012). The GWPs of the scenarios are presented in this manner in Fig. 6. Scenarios 4.2 and 4.1 clearly had the lowest GWPs, whereas the GWPs of the Scenarios 3.1 and 0 were the highest. The GWPs of the other

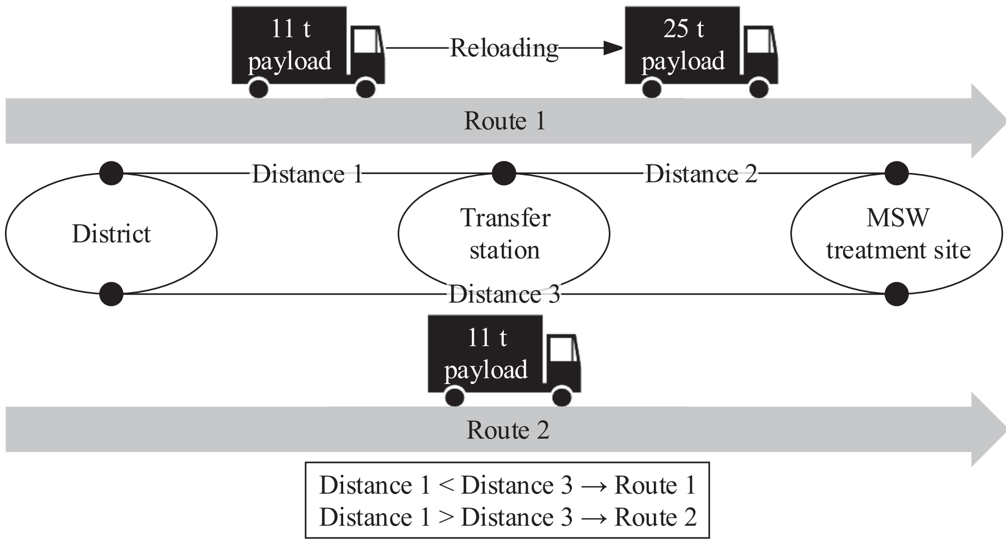


Fig. 5. Calculation principles for transportation distances.

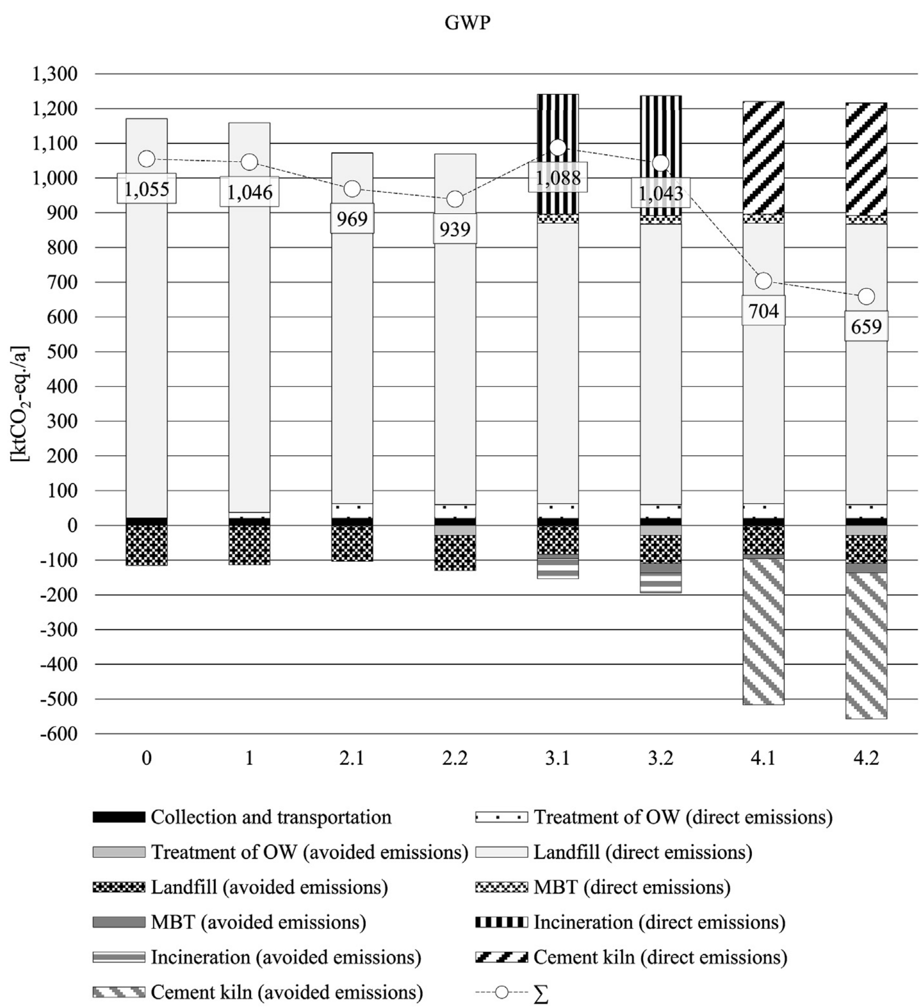


Fig. 6. GWPs of the studied scenarios.

scenarios (Scenarios 1, 2.1, 2.2 and 3.2) were lower compared to the baseline scenario (Scenario 0) but not significantly. It is noteworthy that the MBT of MSW and incineration of RDF (Scenario 3) did not decrease the GWP of MSW management in São Paulo due to the average electricity production in Brazil (approximately 75% hydropower) – quite the contrary. Indeed, electricity production from

RDF generated notably more emissions compared to the average electricity production in Brazil. In other words, the direct emissions of electricity production from RDF incineration outweighed the avoided emissions from electricity substitution (average electricity production in Brazil), which led to an unfavorable outcome for utilization of the RDF in waste incineration plants. Therefore, RDF should rather be utilized in cement production (Scenario 4). As regards different treatment options for separately collected organic waste, the GWP results indicate that AD (Scenarios 2.2, 3.2 and 4.2) is better option than composting (Scenarios 2.1, 3.1 and 4.1). Home composting of organic waste (Scenario 1) decreased the GWP of MSW management slightly.

The APs of the scenarios are presented in Fig. 7. Scenarios 4.2 and 4.1 had the lowest APs, while the APs of Scenarios 3.1 and 3.2 were the highest. It is noteworthy that the APs of all scenarios, except Scenarios 3.1 and 3.2, were negative, i.e. avoided emissions were greater than direct emissions, mainly due to electricity substitution. The results matched observations found in the GWP category – the MBT of MSW and incineration of RDF are not beneficial in this impact category either due to the low amount of avoided emissions resulting from electricity substitution and, respectively, the high amount of direct emissions generated in the incineration process. Combustion in a cement kiln is therefore a better utilization option for RDF than waste incineration for electricity generation in this regard, too. The AP of the baseline scenario was also negative, i.e. beneficial for the environment. The landfill processes inflicted considerably less direct emissions (e.g. the use of bulldozers) compared to the avoided emissions achieved in electricity production from LFG. As in the GWP impact category, it was more beneficial for the separately collected organic waste to be anaerobically digested rather than composted. The composting of organic waste, including home composting, increased the AP of MSW management compared to Scenario 0.

The EPs of the scenarios are presented in Fig. 8. As can be seen, the results were consistent with the previous main findings in the GWP and AP impact categories: AD is a better treatment option for

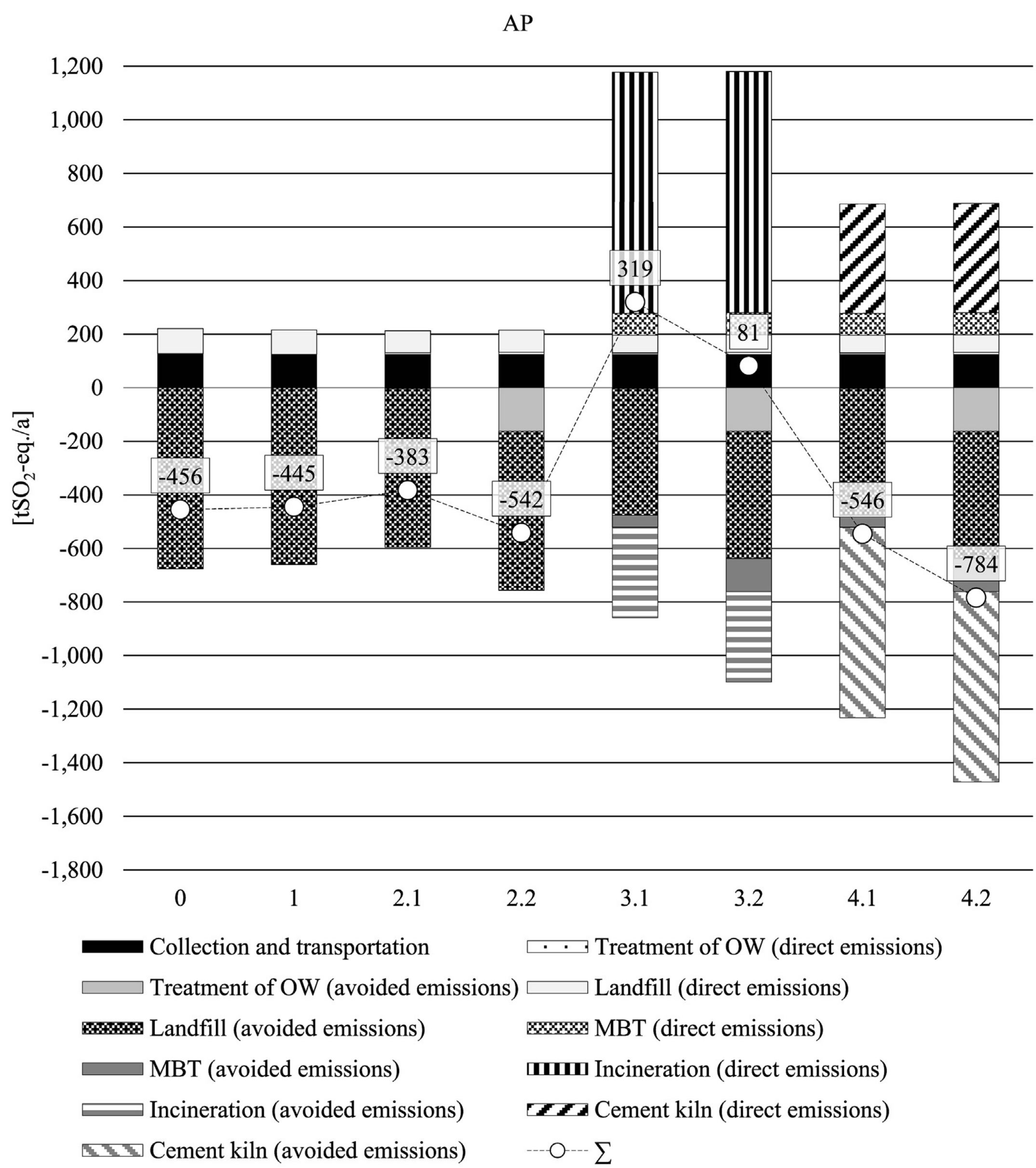


Fig. 7. APs of the studied scenarios.

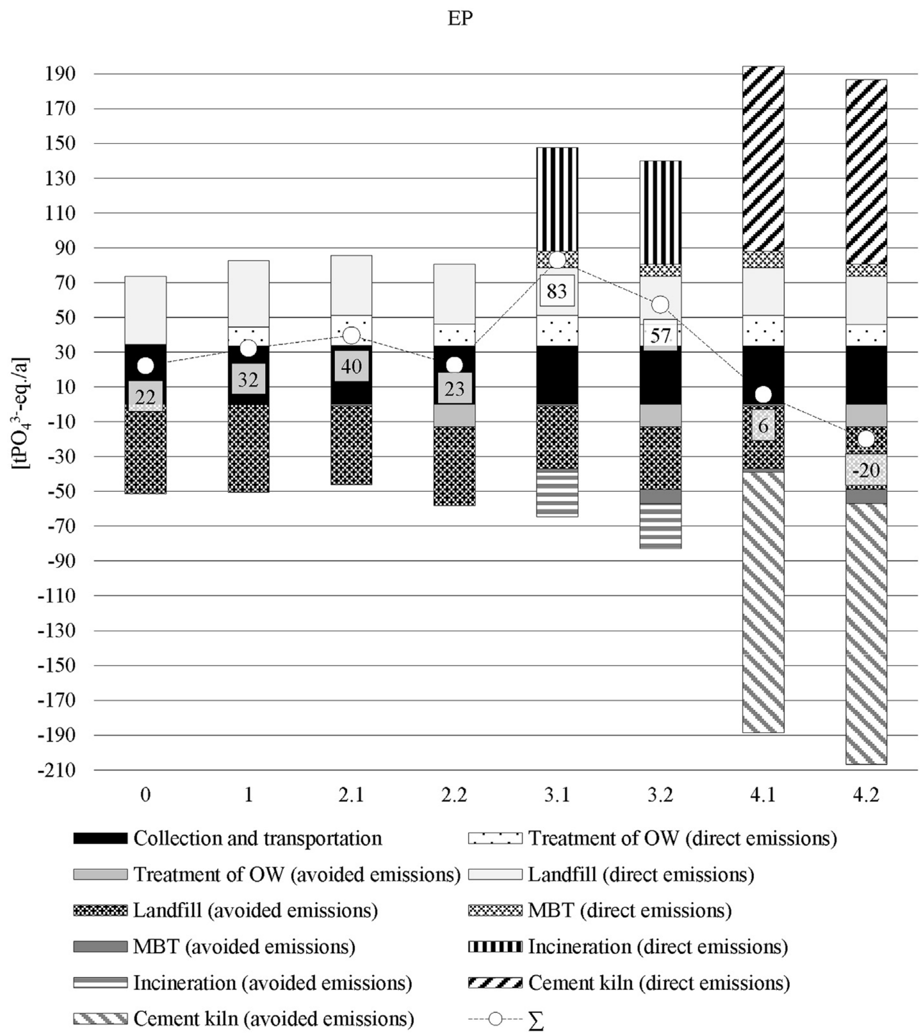


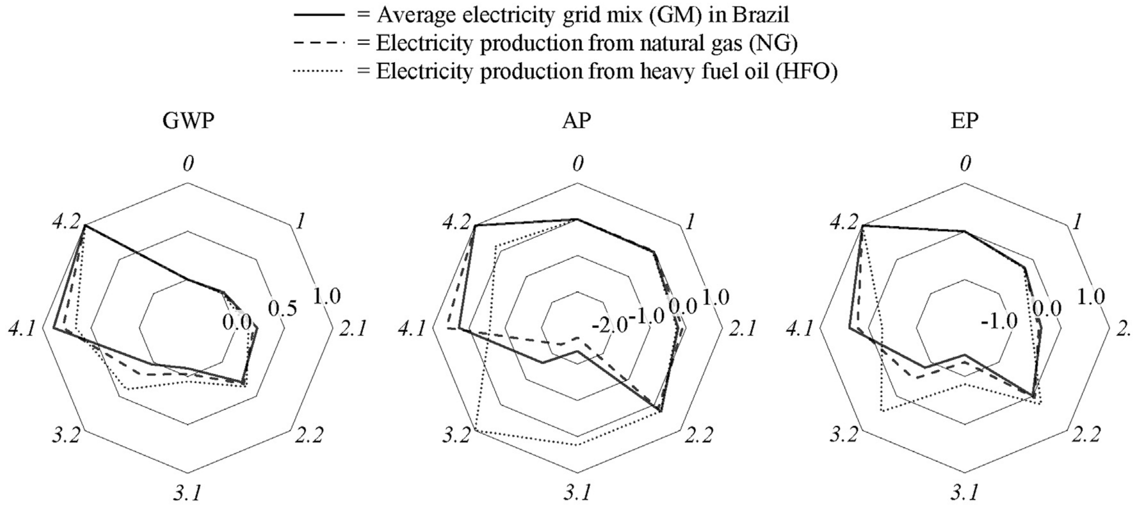
Fig. 8. The EPs of the scenarios.

separately collected organic waste, and usage in cement production is a better utilization option for RDF than incineration. As in the AP impact category, the home composting of organic waste increased the EP of MSW management. However, in this regard, the results were not consistent across the impact categories because home composting decreased the GWP of MSW management.

3.2. Sensitivity analysis

The modeling assumption regarding the kind of electricity production substituted by electricity production from MSW was crucial in terms of the total results in all the impact categories. In the study, it was assumed that the electricity produced would substitute average electricity production in Brazil, which is mainly (~75%) hydropower. Instead of average electricity production, the produced electricity could also substitute marginal energy production. Natural gas is regarded as the most likely fuel for marginal electricity production in Brazil in the foreseeable future (Bernstad Saraiva et al., 2017). Natural gas, as the second largest energy source after hydropower, constitutes a rather large proportion (8.5%) of the average electricity production mix in Brazil. Therefore, it is reasonable to select it for sensitivity analysis as an alternative substituted electricity production. In addition to natural gas, heavy fuel oil was chosen as another alternative energy source for electricity substitution in sensitivity analysis. Heavy fuel oil is the fourth largest energy source (3.6%) in the average electricity production mix in Brazil and is environmentally the most unfavorable (GWP, AP and EP impact categories) alternative of the main energy sources in average electricity production in Brazil. Therefore, it presents simultaneously the worst-case scenario for electricity production and the best-case scenario for electricity substitution – the more avoided emissions resulting from electricity substitution, the more favorable the outcome for electricity production from MSW.

The influence of different electricity substitution options on the results was investigated by determining the weighted results of the scenarios with alternative energy sources (average electricity production mix versus natural gas and heavy fuel oil). Thus, the ranking between the scenarios with different electricity substitution assumptions can be identified. The aim was to find out whether different electricity substitution assumptions make certain treatment methods (e.g. incineration) environmentally more favorable relative to the baseline scenario. The results were weighted relative to the result of the baseline scenario, Scenario 0 (see Fig. 9). The result of Scenario 0 is zero (0.0). If the relatively weighted result (RWR) of a given scenario is > 0.0, the scenario is a better option than Scenario 0. Respectively, if the RWR of a given scenario is < 0.0, the scenario is worse option than Scenario 0. Thus,



Scenario	RWR								
	GWP			AP			EP		
	GM	NG	HFO	GM	NG	HFO	GM	NG	HFO
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.02	0.02	0.01	-0.03	-0.01	-0.05	-0.24	-0.24	-0.26
2.1	0.22	0.18	0.13	-0.22	-0.10	-0.26	-0.41	-0.47	-0.62
2.2	0.29	0.32	0.36	0.26	0.15	0.25	-0.01	0.05	0.24
3.1	-0.08	-0.03	0.05	-2.36	-2.73	0.24	-1.44	-1.29	-0.84
3.2	0.03	0.18	0.40	-1.64	-2.35	1.00	-0.83	-0.51	0.45
4.1	0.89	0.79	0.66	0.27	0.62	-0.58	0.39	0.22	-0.29
4.2	1.00	1.00	1.00	1.00	1.00	0.19	1.00	1.00	1.00

Fig. 9. Relatively weighted results (RWRs) of the study with different choices for substituted electricity.

the maximum of RWRs is 1.0 in each impact category. If the RWR of a given scenario is 1.0, this implies that the scenario is environmentally the most favorable of all the scenarios in a given impact category. The RWRs were calculated using the following equation:

$$\textit{Relatively weighted result } (RWR) = \frac{Result(Scenario_0) - Result(Scenario_i)}{Max\Delta} \quad (2)$$

where Result ($Scenario_0$) = The net result of the baseline scenario (Scenario 0) in a given impact category;

Result ($Scenario_i$) = The net result of a given scenario in a given impact category;
MaxΔ = The maximum difference between the result of the baseline scenario (Scenario 0) and the results of the scenario with the lowest environmental impacts in a given impact category.

The GWPs of the scenarios did not vary significantly when employing different choices for electricity substitution. When the substituted electricity was produced from natural gas instead of the average grid mix in Brazil, the ranking between the scenarios did not vary. In terms of heavy fuel oil, the GWPs of Scenarios 3.1 and 3.2 decreased somewhat, making incineration a more reasonable treatment option for RDF. Nevertheless, Scenarios 4.1 and 4.2 remained as the most favorable scenarios regardless of the electricity substitution choices. Electricity substitution had significantly more influence on the APs of the scenarios. The ranking of the scenarios remained the same when the substituted electricity was produced by natural gas. However, the ranking of the scenarios changed substantially when the substituted electricity was produced by heavy fuel oil. The APs of Scenarios 3.2 and 3.1 decreased significantly, making incineration a more favorable utilization option for RDF than cement production. In terms of the EPs of the scenarios, variations in the electricity substitution assumptions did not have such a notable influence on the ranking of the scenarios. When substituted electricity was produced with heavy fuel oil, the EP of Scenario 3.2 was the second lowest and Scenario 4.2 remained the most viable option. The different modeling assumptions used for electricity substitution did not have an influence on the organic waste treatment options: AD was the better treatment option for organic waste than composting regardless of the changes. Similar sensitivity analysis has been carried by Goulart Coelho and Lange (2016). In their study, variations in the electricity grid mix did not have a notable influence on the results: the ranking of the scenarios remained the same despite the changes. However, it should be noted that the changes employed in their study were more subtle since they varied the shares of different energy sources in the average electricity grid mix. Therefore, the two studies are not fully comparable in this regard.

The collection rate of LFG is a key parameter of landfilling; it typically has a major influence on the total results particularly in the GWP impact category (Liikanen et al., 2017). Therefore, this study employed different LFG collection rates in the sensitivity analysis in order to discover whether the results would vary if the LFG collection rates were lower. In the modeling, the LFG collection rate was 80% in the CTL landfill and 64% in the CTVA Caieiras landfill. These values are somewhat higher than typically found in Brazil. For instance, Mendes et al. (2004) and Bernstad Saraiva et al.

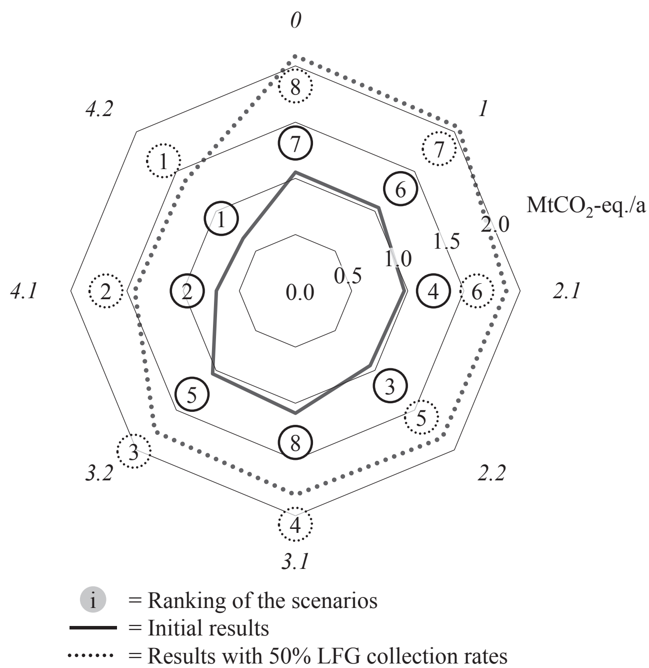


Fig. 10. Sensitivity analysis results with 50% LFG collection rates in the GWP impact category.

(2017) employed 50% LFG collection rates in their LCA studies (São Paulo and Rio de Janeiro were the case areas in these studies). Consequently, a 50% collection rate for LFG in both landfills was also applied in the sensitivity analysis (see Fig. 10, where the results of the sensitivity analysis are presented for GWP).

Lower LFG collection rates had a noteworthy influence on the GWPs of the scenarios. The incineration of RDF (Scenario 3) improved substantially in this regard – the GWPs of Scenarios 3.2 and 3.1 were the third and fourth lowest, respectively. However, the main findings of the results remained the same: (1) AD is a more favorable treatment option for organic waste than composting, and (2) RDF usage in a cement kiln is a more favorable utilization option than incineration. It should also be noted that the GWP of every alternative scenario was lower than the baseline scenario. In terms of the AP and EP impact categories, lower LFG collection rates did not have a notable influence on the results – the ranking of the scenarios remained the same.

3.3. Discussion

The results indicated that of the scenarios assessed in the study, the environmental impacts of MSW management in São Paulo can be most effectively decreased by AD of the organic waste and MBT of the residual MSW on condition that the produced RDF is utilized in cement production. The home composting of organic waste was beneficial from the GWP point of view. Home composting had, however, the opposite effect in the AP and EP impact categories, indicating a need to analyze the results further by for example weighting (EN ISO 14044, 2006) or multi-criteria decision analysis, which has been applied in similar studies (e.g. Angelo et al., 2017). Nevertheless, home composting can diminish the costs of MSW management activities if it decreases collection frequencies since collection is typically a significant cost factor in MSW management (Oliveira et al., 2017). Therefore, current activities promoting home composting in São Paulo (Composta São Paulo, 2017) are justified.

Case area-specific conditions and characteristics have a significant influence on the environmental impacts of different MSW treatment methods since the environmental impacts of the surrounding systems often override the environmental impacts of the treatment processes (Ekvall et al., 2007). Electricity production and substitution is an example of this phenomenon. In Brazil, where average electricity production is dominated by hydropower, which has rather low environmental impacts, the incineration of MSW is not particularly favorable in terms of the environmental impacts assessed in the study due to the low amount of avoided emissions resulting from electricity substitution. Instead of the average electricity grid mix, electricity produced from MSW could also substitute marginal electricity production (e.g. electricity production from natural gas). The effect of different assumptions regarding electricity substitution was assessed, and it was found that the incineration of MSW is more favorable relative to landfilling when other electricity production (more precisely electricity production from natural gas or heavy fuel oil) is substituted. One exception was that the AP of incineration increased in relation to landfilling when electricity produced by natural gas was substituted instead of average grid mix in Brazil. Therefore, in terms of the environmental performance of different MSW treatment methods (particularly incineration), electricity substitution can be a determining factor in LCA studies.

Data uncertainty and variability is inherently part of MSW management LCA studies (Clavreul et al., 2012). This study is no exception. Data uncertainty was assessed by way of an example – LFG collection efficiency. The LFG collection rates employed in the study were higher than typically employed in LCA studies with similar characteristics. Therefore, it was investigated whether lower LFG collection rates would have a significant influence on the results of the study. The ranking of the scenarios in the GWP impact category changed notably when 50% LFG collection rates were applied instead of the initial rates (80% and 64%). The main reason for this change was that the incineration of RDF became more favorable when the environmental impacts of landfilling increased. Nevertheless, the main findings of the study remained the same regardless of the change.

The results of the study are in line with previous literature. Based on this study and other literature studies (e.g. Goulart Coelho and Lange, 2016; Mendes et al., 2003; Soares and Martins, 2017) a consensus can start to be formed regarding the environmentally most favorable treatment method for organic waste. In terms of the environmental impacts of incineration and landfilling, this study and other studies clearly indicate that incineration is not as favorable in Brazil as in other countries (e.g. China) due to the rather low amount of avoided emissions resulting from electricity substitution (e.g. Goulart Coelho and Lange, 2016; Mendes et al., 2004). However, as the sensitivity analysis of the study demonstrated, various factors have an influence on the environmental performance of incineration. It should be particularly kept in mind when interpreting the results of MSW management LCA studies.

4. Conclusions

Landfill disposal has thus far been the predominant treatment method for MSW in São Paulo city. Environmentally sustainable development of MSW management in São Paulo, however, necessitates a stepwise reduction of landfilling. Stepwise improvements towards more environmentally sustainable MSW management in São Paulo were introduced and their environmental impacts investigated. The results indicated that of the proposed treatment alternatives, environmental impacts of MSW management in São Paulo can be most effectively decreased by anaerobic digestion of source separated organic waste and MBT of MSW, on condition that the produced RDF is utilized in cement production as a substitute for coal. The study focused solely on potential treatment alternatives for generated MSW, and therefore other viewpoints of environmentally sustainable MSW management, such as waste prevention and reuse, were not taken into account. These viewpoints are, however, important part of environmentally sustainable MSW management, and should be prioritized before conventional MSW treatment methods. The results of the study provide guidelines for decision- and policy-making from the environmental point of view. The results of the study can be utilized in further studies together with social and economic impact assessment to find the overall sustainability of different MSW management alternatives in the case area, and to provide insight into developing MSW management in other areas, too.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.06.005.

References

AMLURB, 2016. Interview in 13.9.2016 and Data Received Afterwards.
Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2012. Home composting as an alternative treatment option for organic household waste in Denmark: an environmental assessment using life cycle assessment-modelling. Waste Manag. 32 (1), 31–40. https://doi.org/10.1016/j.wasman.2011.09.014.
Angelidaki, I., Chen, X., Cui, J., Kaparaju, P., Ellegaard, L., 2006. Thermophilic anaerobic digestion of source-sorted organic fraction of household municipal solid waste: start-up procedure for continuously stirred tank reactor. Water Res. 40 (14), 2621–2628. https://doi.org/10.1016/j.watres.2006.05.015.
Angelo, A.C.M., Saraiva, A.B., Clímaco, J.C.N., Infante, C.E., Valle, R., 2017. Life Cycle Assessment and Multi-criteria Decision Analysis: selection of a strategy for domestic food waste management in Rio de Janeiro. J. Clean. Prod. 143, 744–756. https://doi.org/10.1016/j.jclepro.2016.12.049.
Astrup, T., Møller, J., Thilde, F., 2009. Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27 (8), 789–799.
Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 30 (3), 254–266. https://doi.org/10.1016/j.biombioe.2005.11.011.
Bernstad Saraiva, A., Souza, R.G., Valle, R.A.B., 2017. Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro - investigating the influence of an attributional or consequential approach. Waste Manag. 68, 701–710. https://doi.org/10.1016/j.wasman.2017.07.002.
Birgisdóttir, H., Pihl, K.A., Bhander, G., Hauschild, M.Z., Christensen, T.H., 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. Transport. Res. Transport Environ. 11 (5), 358–368. https://doi.org/10.1016/j.trd.2006.07.001.
Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27 (8), 800–812.
Brown, S., Kruger, C., Subler, S., 2008. Greenhouse gas balance for composting operations. J. Environ. Qual. 37 (4), 1396. https://doi.org/10.2134/jeq2007.0453.
CCAC, 2015a. Solid Waste Management City Profile - São Paulo, Brazil. www.iswa.org/fileadmin/galleries/Project Grant/CCAC/City_Profile_Sao_Paulo_FINAL.pdf. (Accessed 24 May 2017).
CCAC, 2015b. CCAC MSW City Action Plan. www.iswa.org/fileadmin/galleries/Project Grant/CCAC/City_Action_Plan_Sao_Paulo_approved_AMLURB.pdf. (Accessed 24 May 2017).
Clavreul, J., Guyonnet, D., Christensen, T.H., 2012. Quantifying uncertainty in LCA-modelling of waste management systems. Waste Manag. 32 (12), 2482–2495. https://doi.org/10.1016/j.wasman.2012.07.008.
Composta São Paulo, 2017. Composta São Paulo, Um movimento por uma cidade mais sustentável. www.compostasaopaulo.eco.br/. (Accessed 24 May 2017).
Consonni, S., Giugliano, M., Grosso, M., 2005. Alternative strategies for energy recovery from municipal solid waste: Part A: mass and energy balances. Waste Manag. 25 (2), 123–135. https://doi.org/10.1016/j.wasman.2004.09.007.
Damgaard, A., Larsen, A.W., Christensen, T.H., 2009. Recycling of metals: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27 (8), 773–780.
Di Lonardo, M.C., Lombardi, F., Gavasci, R., 2012. Characterization of MBT plants input and outputs: a review. Rev. Environ. Sci. Biotechnol. 11 (4), 353–363. https://doi.org/10.1007/s11157-012-9299-2.
EC-JRC, 2010. General guide for life cycle assessment - detailed guidance. In: ILCD Handbook -International Reference Life Cycle Data System, first ed. Publications Office of the European Union, Luxembourg. EUR 24708 EN.
Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What life-cycle assessment does and does not do in assessments of waste management. Waste Manag. 27 (8), 989–996. https://doi.org/10.1016/j.wasman.2007.02.015.
EN ISO 14040, 2006. Environmental Management. Life Cycle Assessment. Principles and framework. European Committee for Standardization, Brussels, Belgium.
EN ISO 14044, 2006. Environmental Management. Life Cycle Assessment. Requirements and Guidelines. European Committee for Standardization, Brussels, Belgium.
Goulart Coelho, L.M., Lange, L.C., 2016. Applying life cycle assessment to support environmentally sustainable waste management strategies in Brazil. Resour. Conserv. Recycl. 128, 438–450. https://doi.org/10.1016/j.resconrec.2016.09.026.
Guerrero, L.A., Maas, G., Hogland, W., 2013. Solid waste management challenges for cities in developing countries. Waste Manag. 33 (1), 220–232. https://doi.org/10.1016/j.wasman.2012.09.008.
Havukainen, J., Zhan, M., Dong, J., Liikanen, M., Deviatkin, I., Li, X., Horttanainen, M., 2017. Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. J. Clean. Prod. 141, 453–461. https://doi.org/10.1016/j.jclepro.2016.09.146.
Hupponen, M., Grönman, K., Horttanainen, M., 2015. How should greenhouse gas emissions be taken into account in the decision making of municipal solid waste management procurements? A case study of the South Karelia region, Finland. Waste Manag. 42, 196–207. https://doi.org/10.1016/j.wasman.2015.03.040.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories, vol. 5. www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html.
Karmperis, A.C., Aravossis, K., Tatsiopoulos, I.P., Sotirchos, A., 2013. Decision support models for solid waste management: review and game-theoretic approaches. Waste Manag. 33 (5), 1290–1301. https://doi.org/10.1016/j.wasman.2013.01.017.
Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014. Review of LCA studies of solid waste management systems – Part I: lessons learned and perspectives. Waste Manag. 34 (3), 573–588. https://doi.org/10.1016/j.wasman.2013.10.045.
Leme, M.M.V., Rocha, M.H., Lora, E.E.S., Venturini, O.J., Lopes, B.M., Ferreira, C.H., 2014. Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. Resour. Conserv. Recycl. 87, 8–20. https://doi.org/10.1016/j.resconrec.2014.03.003.
Liikanen, M., Havukainen, J., Hupponen, M., Horttanainen, M., 2017. Influence of different factors in the life cycle assessment of mixed municipal solid waste management systems – a comparison of case studies in Finland and China. J. Clean. Prod. 154, 389–400. https://doi.org/10.1016/j.jclepro.2017.04.023.
Lino, F.A.M., Ismail, K.A.R., 2011. Energy and environmental potential of solid waste in Brazil. Energy Pol. 39 (6), 3496–3502. https://doi.org/10.1016/j.enpol.2011.03.048.
Mambeli Barros, R., Tiago Filho, G.L., da Silva, T.R., 2014. The electric energy potential of landfill biogas in Brazil. Energy Pol. 65, 150–164. https://doi.org/10.1016/j.enpol.2013.10.028.
Mendes, M.R., Aramaki, T., Hanaki, K., 2003. Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in São Paulo City. Waste Manag. 23 (5), 403–409. https://doi.org/10.1016/S0956-053X(03)00058-8.
Mendes, M.R., Aramaki, T., Hanaki, K., 2004. Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. Resour. Conserv. Recycl. 41 (1), 47–63. https://doi.org/10.1016/j.resconrec.2003.08.003.
Møller, H.B., Sommer, S.G., Ahring, B.K., 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bioresour. Technol. 85 (2), 189–196. https://doi.org/10.1016/S0960-8524(02)00047-0.
Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., 2015. Mass, energy and material balances of SRF production process. Part 3: solid recovered fuel produced from municipal solid waste. Waste Manag. Res. 33 (2), 146–156.
Nielsen, M., Nielsen, O.-K., Thomsen, M., 2010. Emissions from Decentralised CHP Plants 2007. www.dmu.dk/Pub/FR786.pdf. (Accessed 25 September 2017).
Oliveira, L.S.B.L., Oliveira, D.S.B.L., Bezerra, B.S., Silva Pereira, B., Battistelle, R.A.G., 2017. Environmental analysis of organic waste treatment focusing on composting scenarios. J. Clean. Prod. 155, 229–237. https://doi.org/10.1016/j.jclepro.2016.08.093.
Pagans, E., Barrena, R., Font, X., Sánchez, A., 2006. Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere 62 (9), 1534–1542. https://doi.org/10.1016/j.chemosphere.2005.06.044.
Prefeitura de São Paulo, 2014. Plano de Gestão Integrada de Resíduos Sólidos da Cidade de São Paulo (in Portuguese). www.prefeitura.sp.gov.br/cidade/secretarias/upload/servicos/arquivos/PGIRS-2014.pdf. (Accessed 24 May 2017).
Santos, S.M., Silva, M.M., Melo, R.M., Gavazza, S., Florencio, L., Kato, M.T., 2017. Multi-criteria analysis for municipal solid waste management in a Brazilian metropolitan area. Environ. Monit. Assess. 189, 561. https://doi.org/10.1007/s10661-017-6283-x.
Soares, F.R., Martins, G., 2017. Using life cycle assessment to compare environmental

impacts of different waste to energy options for Sao Paulo's municipal solid waste. J. Solid Waste Technol. Manag. 43 (1), 36–46.

Thinkstep, 2016. GaBi Databases 2016 Edition - Upgrades & Improvements. www.gabi-software.com/fileadmin/GaBi_Databases/Database_Upgrade_2016_Upgrades_and_improvements.pdf. (Accessed 26 September 2017).

Thinkstep, 2017. GaBi LCA Software. www.thinkstep.com/software/gabi-lca. (Accessed 25 September 2017).

Turner, D.A., Williams, I.D., Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. J. Clean. Prod. 129, 234–248. https://doi.org/10.1016/j.jclepro.2016.04.077.

Waste Atlas, 2017. Waste Atlas. www.atlas.d-waste.com/. (Accessed 23 May 2017).

World Bank, 2012. What a Waste – a Global Review of Solid Waste Management. Urban Development Series, March 2012, No. 15. Washington, DC, 20433, USA. siteresources. worldbank.org/INTURBANDEVELOPMENT/Resources/336387–1334852610766/What_a_Waste2012_Final.pdf. (Accessed 23 May 2017).

World Bank, 2017a. Brazil Overview. www.worldbank.org/en/country/brazil/overview. (Accessed 22 August 2017).

World Bank, 2017b. Brazil | Data. data.worldbank.org/country/brazil. (Accessed 24 October 2017).