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Life cycle comparative assessment of pet bottle waste management options: A case study for the city of Bauru, Brazil

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ABSTRACT

This study analyzed the environmental impacts of nine scenarios for Polyethylene Terephthalate (PET) bottle waste disposal, in the city of Bauru, Brazil. Nine scenarios were considered in this study: (1) current (base) scenario (96.4% of PET waste is sent to landfill, 3.6% is sent to sorting cooperatives); (2) 50% to sorting cooperatives, 50% to landfill; (3) 50% to sorting cooperatives, 50% to incineration; (4) 50% to landfill, 50% to incineration; (5) 100% to sorting cooperatives (keeping the current collection distribution); (6) 100% to landfill; (7) 100% to incineration; (8) and (9) 100% sent to sorting cooperatives, with changes in the collection scheme. Life cycle assessment was implemented to compute the impacts for each scenario and compare their environmental performances. The results have shown that recycling is a better option than incineration across all impact categories analyzed. Landfilling had lower net impacts than incineration in all categories, except for ozone depletion and freshwater eutrophication. All recycling scenarios proposed outperformed the current scenario in all impact categories. Even though recycling presents itself as an environmentally-promising alternative, much work still needs to be done for its successful implementation, such as promoting source-separation at home and improving the management strategies of recycling cooperatives, including additional funding and training to support an increased sorting capacity.

1. Introduction

In a consumer- and profit-oriented economy, industries have been expanding rapidly, often with a lack of accompanying environmental policies to manage and regulate the impacts caused by increased production. Equally concerning are the impacts resulting from the use and disposal of the products manufactured. With the widespread use of plastics in everyday materials, it becomes particularly important to study the environmental and health effects associated with the plastics industry. One type of plastic that has become extremely popular is polyethylene terephthalate (PET), which has ample utilization in the beverage and textile industries. In 2017, 30.3 million tons of PET were produced, and more than 50% of the synthetic fibers and bottles produced worldwide were made of it (PlasticsInsight, 2019). PET is widely attractive due to its durability, strength, stability, low permeability (which makes it safe for containing food items), and ease of processing and handling (Webb et al., 2013).

Traditional production of PET is most commonly carried out by reacting ethylene glycol (EG) with terephthalic acid (TPA) in a transesterification reaction, followed by a series of polymerization steps, the number of which depends on the required molecular weight for the application (Webb et al., 2013). To produce food-grade PET resins, an additional solid-phase polymerization step is required (Webb et al., 2013; Kägi et al., 2017). The resins are then heated and molten to give the desired shape via extrusion, injection, or blow molding. It has been reported that production of one kg PET resin requires 70–83 MJ of thermal energy (Gleick et al., 2009) and releases 2.44 kg CO_2e to the atmosphere (Webb et al., 2013). Moreover, the chemicals used to produce the PET resin are fossil-based (Benavides et al., 2018); TPA is produced via oxidation of paraxylene with acetic acid, and EG production starts with ethylene (Benavides et al., 2018).

Despite the robustness and durability of PET, the use phase of this material is usually short, and the same qualities that make it attractive as packing material, also make it extremely resistant to chemical degradation, when disposed of. This resistance to

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degradation, associated with high production volumes, makes the issue of adequate PET disposal very relevant (Gomes et al., 2019). Studies have shown that when PET is landfilled only 1–5% of the carbon in the plastic degrades in 150 years; and the remaining carbon could take thousands, or perhaps millions of years to be released (Sundqvist, 1999). Additionally, PET bottles can release volatile organic compounds (VOCs) to both air and water (leachate), when landfilled (Webb et al., 2013).

Investigating the post-consumption phase of PET bottles is important, since it addresses the issues related (1) to the PET fossil production process, which can be avoided if waste PET is recovered and recycled and (2) to its final disposal. Reverse logistics is defined by the Brazilian National Policy on Solid Waste (NPSW) as a tool for economic and social development, characterized by a group of actions, procedures and measures aimed at either making the collection of solid waste and its recycling to industry for reuse in its own or other productive cycles viable or, if such recycling is not possible, disposing of the waste in an environmentally adequate way (Brasil, 2010). Life Cycle Assessment (LCA) approach is an important tool to evaluate the environmental impacts of different management options for reverse logistics of PET bottles.

Many studies have already considered several aspects of post-consumption of PET, such as several disposal mechanisms (landfilling, incineration, chemical recycling) and alternative materials (other plastics, glass, metal). A study carried out by Foolmaun and Ramjeeawon in Mauritius has shown that considering the environmental and social dimensions of sustainability, mechanical recycling of 75% waste PET to produce PET flakes, with the remaining 25% being landfill was a better waste disposal strategy than 100% landfilling, 75% incineration (25% landfilled), and 40% recycling (60% landfilled) (Foolmaun and Ramjeewon, 2013). Kuczenski and Geyer, who studied the reverse logistics of PET in California, US, indicate that recycling (as opposed to landfilling) could reduce environmental impacts of several categories, notably global warming, acidification, and ozone depletion (Kuczenski & Geyer, 2013). Several studies also pointed out that the largest benefit of PET recycling is the impact offsets due to replacement of fossil-based PET (Michaud et al., 2010; Park & Gupta, 2015; Kang et al., 2017). Another benefit of recycling PET would be to increase landfill operational lifetime, by reducing the volume of waste that goes to the landfill. The best PET disposal practices will depend on the country's energy demand, recycling level, and available infrastructure for recycling. Thus, the specific context of the country should be taken into consideration.

There is indication that evaluation of PET end-of-life scenarios is lacking for developing countries (Gomes et al., 2019). Indeed, there's scarce data available for South America. Moreover, most studies usually focus on only two impact categories, energy consumption and global warming potential (Gomes et al., 2019). Therefore, the purpose of this study was to assess several environmental impacts associated with PET bottle waste disposal and recycling in Brazil, using an LCA approach. The city of Bauru, in the state of São Paulo, was used as a case study area. Different scenarios were considered to evaluate the impacts of different waste management options, including mechanical recycling, landfilling and incineration. PET waste collection and transportation was also included in the analysis. The results from this assessment can guide policy-makers in making sustainable decisions regarding waste management in the municipality of Bauru, and other cities with similar waste management strategies.

2. PET waste management policy in Brazil

In Brazil, solutions to the issues related to the post-consumption phase of PET have been proposed by (1) the National Sanitary Surveillance Agency (ANVISA) PET-PCR resolution n. 20/2008 (ANVISA, 2008) and (2) the National Policy on Solid Waste (NPSW). Waste generation in Brazil has increased 29% from 2003 to 2014, which is five times more than the populational growth (6%) for the same period (ABRELPE, 2014). Forty one percent of the Brazilian municipal solid waste (MSW) is either landfilled or dumped (ABRELPE, 2014). When it comes to PET, Brazil has one of the highest consumption rates in the world (Coelho et al., 2011), with 840 thousand tons consumed in 2016, 90% of which were PET bottles (ABIPET, 2013). Current PET recycling rate is 51% (ABIPET, 2016), and the main barrier to recycling is the traditional selective collection system, mostly because a culture of waste separation at home is not practiced or common (Formigoni et al., 2014). Another barrier specific to Bauru, but which is likely to apply to many other municipalities as well, is that material recovery facilities (called sorting cooperatives), which are responsible for sorting recyclable waste, often work at full capacity, in poor conditions, and with undertrained staff, greatly reducing the sorting capacity (Plano Municipal Saneamento Básico, 2016).

The establishment of standards for the production of post-consumer recyclable PET (PET-PCR), implemented via ANVISA's resolution no. 20/2008, is an important step for the reduction of fossil-based PET production. With this, companies that produce food-grade recycled PET-PCR materials can get certified and have their products commercialized. The recycled PET can then replace fossil-based PET, by re-entering the PET market. Once there, it can be used to produce the same product (closed-loop) or a different product (open-loop). Currently, one quarter of the recycled PET in Brazil is used directly in PET bottle production (B2B), while another quarter is used for textile production, around 30% is used for the production of unsaturated alkyl resins, and the remaining is used in the production of other types of packages, such as laminates and sheets (ABIPET, 2016). However, the B2B production is expected to increase 60% in the following years (ABIPET, 2016), making this application the most likely one in the near future.

The NPSW was created to improve the solid waste management situation in Brazil by reducing waste generation and establishing a shared responsibility among waste producers – manufacturers, importers, distributors, merchants, residents, and operators of solid waste management services – concerning the reserve logistics of waste and post-consumer packages (Ministério do Meio Ambiente, 2015). Selective collection is the most fragile link in PET waste recycling, since it depends on the population's ability and willingness to separate recyclables from organic waste, and on the municipalities to collect and redirect the recyclable waste for sorting at the cooperatives (Formigoni et al., 2014).

The shared responsibility proposed by the NPSW can help strengthen current selective collection practices by stimulating society to participate and engage in the collection process. This is exemplified by the creation of Ecopoints, locations around the city where people and small businesses can dispose of recyclables and other waste types, and by selective collection offered by the cooperatives themselves. Even though these actions still represent a small percentage of total selective waste collection, they are important as education measures and may become more common as a result of the growing awareness of the population and government officials.

2.1. Study area and current situation

The city of Bauru, in the state of São Paulo, Brazil is the study area. In 2019, 96,300 metric tons (t) of residential Municipal Solid Waste (MSW) was collected by the municipality (see Table 1). With an estimated population of 376,818 inhabitants in 2019 (IBGE, 2019), the per capita MSW generation rate is about 0.7 kg/day.person. There are four ways in which MSW (or some of its components)

Table 1
Municipal solid waste (MSW) and PET waste collected in 2019.

	EMDURB conventional	EMDURB selective*	ASCAM*	Ecopoints – SEMMA**	Total
MSW (t)	93,600	1,750	204	720	96,300
% PET in MSW	5.21	5.94	8.65	8.36	5.4
PET (t)	4,880	104	18	60	5,062
% of Total PET	96.4	2.1	0.3	1.2	100

* MSW collected includes only recyclables (papers, metals, glass, plastics).
** MSW collected includes recyclables, electronics, and some organic wastes (used oil).

can be collected in the city: (1) conventional collection (mixed waste collection) carried out by the city's urban and rural development company (EMDURB); (2) selective collection of recyclable materials carried out by EMDURB; (3) selective collection of recyclable materials carried out by the city's recyclable's collectors association (ASCAM); and (4) through Ecopoints, specific locations in the city where the population can drop off some types of wastes (including recyclables) and from where waste is transported to an appropriate place for final disposal or reuse. During the time data for this study was collected, the transport from the Ecopoints was managed by the municipality's environmental department (SEMMA). The amounts of MSW and percentage of polyethylene terephthalate (PET) waste in the MSW for these four collection methods are presented in Table 1. The data presented in Table 1 were obtained via interviews with EMDURB and SEMMA and onsite at ASCAM.

3. Methodology

The ISO 14040 (2006) metrics provide the guidelines for conducting a life cycle assessment. It divides the LCA into four parts: goal and scope definition, inventory analysis, impact assessment, and interpretation.

3.1. Goal and scope

The functional unit is 1 metric ton (t) of PET waste, and the total PET waste collected in the city of Bauru in 2019 was used to calculate the percentages of the reference flow per 1 metric ton. The term "PET waste" refers to the PET bottle only, excluding the plastic cap, label, and any remaining residues in the bottle. The goal of this LCA study was to assess the environmental impacts of different management options for PET waste by considering several scenarios, as described in Section 3.3.

3.2. System boundaries

The system is not "cradle to grave", because it starts from the point PET waste is discarded by the residents and ends when its value and utility are recovered, or it is disposed of. The system's boundary includes collection and transportation of PET waste, its recycling or disposal, and replacement of fossil-based PET granulate (by the esterification of ethylene glycol and terephthalic acid process), when applicable. The inputs to the system are: material flows, such as PET waste, diesel fuel for collection and transportation trucks and process equipment, and materials for construction of facilities and waste management installations; and energy flows, such as electricity and heat for process operations. The outputs from the system are: emissions from collection and transportation trucks and other machines, direct emissions from waste management processes, indirect emissions from construction of facilities and electricity/heat production, and avoided emissions from the fossil-based production of PET.

The waste management structure in Bauru is currently comprised of the following facilities: 1 wastewater treatment plant (WWTP) (1.26×10^9 L/yr capacity), 8 Ecopoints, 1 public-owned landfill (closed in 2014, but still collecting leachate), and 3 sorting cooperatives. Since the city's landfill is closed, MSW generated in Bauru is currently sent to a private landfill in a neighboring town (Piratininga, SP, Brazil), located 43 km from Bauru. Landfill gas (LFG) is captured and flared, and even though a LFG energy project is being considered, no energy recovery was assumed. The leachate produced in this landfill is stored and transported by trucks to Jundiaí, SP, Brazil (350 km from landfill), where it is treated in a wastewater plant, and the resulting digested sludge, composted in the same facility. PET recycling starts at the sorting cooperatives, were the PET waste is sorted, pressed, and baled. The bales are then bought by recycling companies. In the case of PET, the recycling process to produce food-grade PET consists of cleaning, grinding (to produce flakes), extruding, and chopping to produce granules (or thermoplastic resins). The efficiency of this process was taken as 91% (Kägi et al., 2017). There are only 2 companies in the State of São Paulo that are certified to produced food-grade PET granules (resins) from recycled PET; many others are certified to produce a variety of other food-grade PET materials, starting from either the recycled flakes or the recycled resins (ANVISA, 2020). But since in this study production of granulate PET was assumed to be the replaced process, the transportation distance from the sorting cooperatives to the PET recycling facilities was taken as an average distance to those two companies, one in São Carlos, SP (175 km from Bauru) and the other in Caieiras, SP (335 km from Bauru). Table S1 (in the Data in Brief article) summarizes the transportation distances, including from waste collection (Martin et al., 2020).

Currently, 96.4% of the collected PET waste is sent directly to the landfill, while 3.6% is transported to the sorting cooperatives. The PET sorting efficiency at the cooperatives is 80.4%, and the rejected PET is disposed of in the landfill (data collected from ASCAM). With the recycling efficiency of 91%, only 2.6% of the PET waste in Bauru is effectively recycled, and 97.4% is sent to the landfill. This number is well below the national Brazilian average for PET collection to be recycled, which is 51% (ABIPET, 2016). The waste collected at the Ecopoints has some level of sorting, however due to precarious transportation to the sorting cooperatives, the recyclables are mixed again, and therefore, it was assumed that the PET waste collected at the Ecopoints had the same sorting efficiency as that of the sorting cooperatives. The descriptions of system boundaries for the base scenario are provided in Fig. 1. In the next section, a detailed description for the other 8 scenarios considered will be presented.

3.3. Scenarios description

Nine scenarios were considered in this study: (1) current (base) scenario (96.4% of reference flow is sent to landfill, 3.6% is sent to sorting cooperatives, as presented in Section 3.2.; (2) 50% to sorting cooperatives, 50% to landfill; (3) 50% to sorting cooperatives, 50% to incineration; (4) 50% to landfill, 50% to incineration; (5) 100% to sorting cooperatives (keeping the current collection distribution); (6) 100% to landfill; (7) 100% to incineration, (8) 100% to sorting

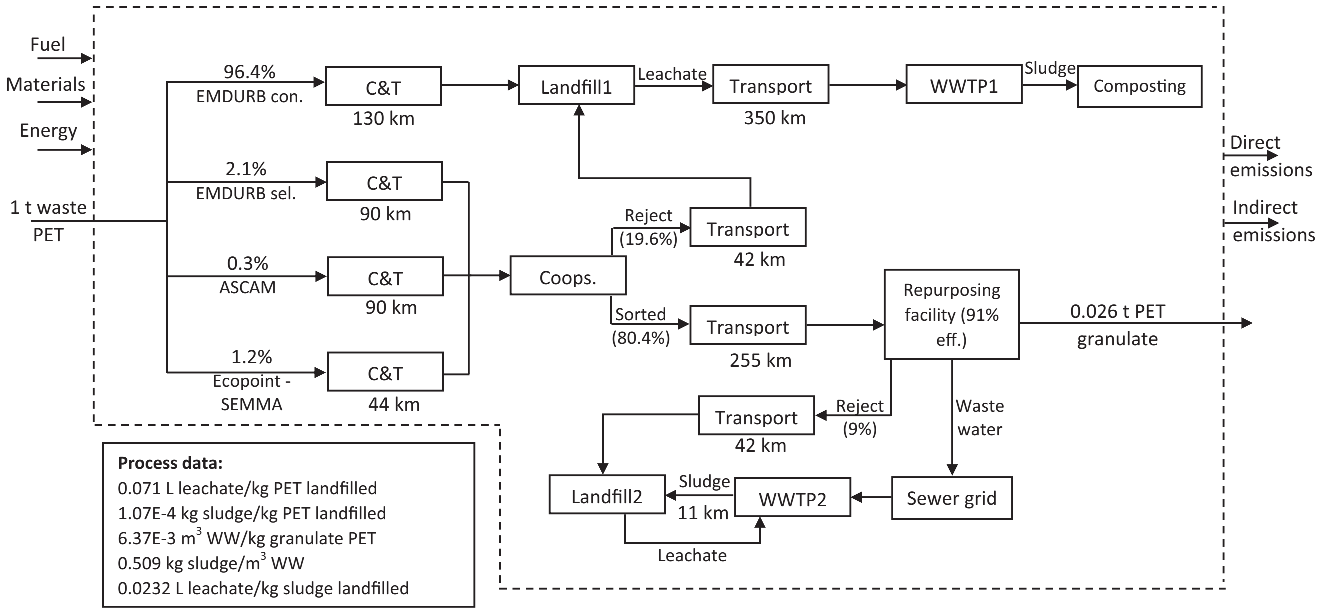

Fig. 1. System boundary for base scenario (S1).

cooperatives (50% collected in Ecopoints, 50% collected by selective collection), (9) 100% to sorting cooperatives (75% collected in Ecopoints, 25% collected by selective collection). The base scenario (scenario 1) was described in Section 3.2. and is schematically depicted in Fig. 1.

The second scenario (scenario 2) proposes an increase to 50% of the collected PET waste sent to the sorting cooperatives (instead of 3.6%), with the remaining of collected PET waste being disposed of directly in the landfill. The capital goods for expanding the sorting cooperatives were considered, since they already work at full capacity (Plano Municipal Saneamento Básico, 2016), and increasing the sorting capacity would require more infrastructure than is currently available. Treatment of wastewater generated during the recycling of PET waste, at the recycling companies, occurs in wastewater treatment plants in the cities where the recycling occurs, and the resulting sludge is landfilled. Construction of a sanitary landfill was also included, since landfills are waste disposal sites that are continuously constructed as more waste is deposited, and also to establish fair comparisons with other scenarios where new infrastructure is needed. Construction of the WWTP for leachate treatment and composting facility (for sludge treatment) were also considered. The PET that is rejected by the sorting cooperatives and recycling facilities (27% of the PET waste sent to sorting cooperatives) is landfilled.

Scenario 3 consists of sending 50% of the PET waste to sorting cooperatives, while the remaining 50% is sent directly to an incineration facility. There's no incineration plant in Bauru, and even though its construction was advised against (Plano Municipal Saneamento Básico, 2014), due to high initial investments, need for large infrastructure for emissions control, reduced workforce when compared to other waste management options, and decreased recycling rates, it was considered in this study due to the energy offsets provided by the combustion of PET waste, which can offer environmental benefits. The energy generated during incineration of PET was estimated using the lower heating value of PET (22.95 MJ/kg), and electricity and heat generation efficiencies during incineration of 15.8% and 28.5%, respectively (Doka, 2013). Since district heating is not a common practice in Brazil, the excess heat produced during incineration, that is not already reutilized in the incineration facility, was assumed to be converted into electricity in a vapor turbine with an efficiency of 45%, resulting in an overall electricity generation efficiency of 28.6%. The slags and residues produced during incineration were assumed to be landfilled, with no leachate production. The incineration facility was assumed to be located 100 km from the landfill. This is the only scenario where the rejected PET from the sorting cooperatives is incinerated, and not landfilled. Collection distances to incineration were assumed to be the same as the collection distances to the landfill.

Scenario 4 proposes a reduction in the amount of PET waste landfilled to 50%, with the remaining PET being incinerated. Landfill and incineration plant constructions, as well as construction of other downstream facilities (WWTP, composting), were considered.

Scenario 5 assumes all PET waste is sent to the sorting cooperatives and keeps the PET collection distribution scheme shown in Table S2 (Martin et al., 2020). This scenario would require separation of recyclables by the population prior to collection, so that all PET could be collected by selective collection. The PET collected by EMDURB conventional collection was assumed to be collected by EMDURB selective. The PET rejected for recycling (both at the sorting cooperatives in Bauru and at the recycling companies in São Carlos/Caieiras) is landfilled. This is an optimistic scenario which considers what would happen if all inhabitants recycled their PET waste.

Scenario 6 assumes all PET waste is landfilled, whereas scenario 7 represents incineration of 100% of PET waste. Scenarios 8 and 9 are similar to scenario 5, with all PET waste being sent to sorting cooperatives, but differ in the collection structure. In scenario 8, 50% of the PET waste is collected in Ecopoints, with the remaining being collected by selective collection (85% carried out by EMDURB, 15% by ASCAM). In scenario 9, the percentage of PET collected from Ecopoints increases to 75%, with the remaining 25% being collected selectively by EMDURB (85%) and ASCAM (15%). For both scenarios, the rejected PET is landfilled.

It is important to point out that transport of PET waste carried out by the population to the Ecopoints is not considered, since it is not possible to account for the transportation distance travelled by all Ecopoint users, or to determine if the trip was exclusively done to the Ecopoint, and not to other purposes including the Ecopoint.

Figs. S1 to S8 in Martin et al. (2020) depict the system boundaries for scenarios 2 to 9.

3.4. Life cycle assessment method

An attributional LCA, with average energies, was used in this study. The software SimaPro 8 ® was used to calculate the environmental impacts from the emissions and processes described in the inventory (see Section 3.5). The method selected in SimaPro was Allocation Default (allocation at the point of substitution in Ecoinvent). The ReCiPe Worldwide Midpoint (Hierarchical) v1.09 method was used for this life cycle assessment (Goedkoop et al., 2009). Even though the ReCiPe method has 18 impact categories, in this paper the following impact categories were assessed: climate change (kg CO_2 eq.), ozone depletion (kg CFC-11 eq.), terrestrial acidification (kg SO_2 eq.), freshwater eutrophication (kg P eq.), human toxicity (kg 1,4-DB eq.), terrestrial ecotoxicity (kg 1,4-DB eq.), and freshwater ecotoxicity (kg 1,4-DB eq.). The result for the other impact categories can be seen in the Data in Brief article associated with this paper (Martin et al., 2020). The impact categories were assessed for 100 years of emissions stemming from the treatment of 1 metric ton of PET waste, based on collection and sorting data for one year (2019). The time period for the technology used in the inventories varied from 1994 to 2018. However, since this paper did not perform a consequential LCA and it was not the scope of this project to quantify uncertainties in the LCI data, the technology gap was not considered.

3.5. Life cycle inventory

Primary data were collected for the energy requirements and material inputs of a sorting cooperative (facility), shown in Table 2, amount of PET waste collected (Table 1), and transportation distances (Table S1 available in the Data in Brief article, Martin et al., 2020).

For collection and transportation, the city's fleet was analyzed to obtain the average truck capacity (around 16–18 t), and year model, which would then indicate the emissions standard to use (EURO 1, 2, 3, 4, 5, or 6), as shown in Table S2 in the Data in Brief article (Martin et al., 2020).

The transportation of reject PET from the cooperatives to the landfill and of slags/residues from incineration to landfill was assumed to be carried out by the fleet from EMDURB conventional collection. The transport of bales from the cooperatives to the recycling company was assumed to occur in a EURO 6 truck, with 16–32 t capacity, and the transport of leachate from landfill to WWTP in Jundiaí by an EURO 5 truck, with 23 t capacity. Emissions inventory for EURO trucks were from Keller (2010).

Table 2
Energy consumption and material inputs for a recycling facility in Bauru (per t waste PET).

Input	Amount	Units
Steel wire drawing, for bales	1.65	kg
Fork-lift fuel LPG**	7	L
Electricity*, conveyor belt	4.47	kWh
Electricity*, press	11.9	kWh
Electricity*, baling	0.13	kWh
Electricity*, auxiliary conveyor belt	1.52	kWh

* Electricity is medium voltage.
** LPG stands for Liquefied Petroleum Gas.

The construction inventory for a materials recycling facility (Kägi et al., 2017), sanitary landfill facility, municipal incineration facility, wastewater treatment plant, sewer grid (Doka, 2007), and composting plant (Nemecek et al., 2007) were obtained from the Ecoinvent v3.6 (2019) inventories for a global geography, since there were no inventories specific to Brazil. Processes corresponding to the global production market for the construction materials were used, since they already account for transportation distances and consider the average production technology employed worldwide, unless a specific production process, widely used in Brazil, was available.

The operation and emissions inventory for a sanitary landfill (Doka, 2007), municipal incineration facility (Doka, 2013; Jungbluth et al., 2007), wastewater treatment plant (Doka, 2008), PET fossil-based production (PlasticsEurope, 2017), and PET recycled production (Kägi et al., 2017) were adapted from the Ecoinvent v3.6 (2019) inventories for a global geography. For the operation phase, whenever possible, adjustments to the processes and energy or material inputs were made to reflect more specifically the technology or conditions in Brazil. For example, electricity was produced in hydroelectric plants, with data specific to the southeastern region of Brazil (where São Paulo state is located) (Bolliger & Bauer, 2007) and heat utilized for PET production from PET waste came from burning wood chips. All energy related data was an average energy data for Brazil, and energy recovery was only considered for incineration scenarios.

The operation inventory for a composting plant was adapted from Cadena et al. (2009), using electricity generation processes that better represent the Brazilian reality. The emissions inventory for a composting plant was obtained from Amlinger et al. (2008).

Table S3 in the Data in Brief article summarizes the inventory used for this study, as well as the adjustments made (Martin et al., 2020).

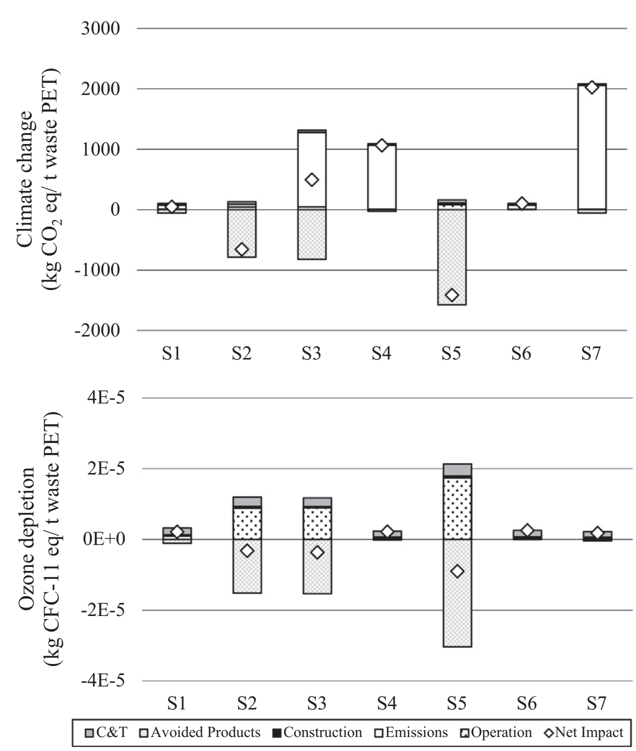

Fig. 2. Total impact for climate change and ozone depletion categories and breakdown of contributions.

4. Results

Impact values for the climate change and ozone depletion categories are shown for scenarios S1 through S7 in Fig. 2. For terrestrial acidification and freshwater eutrophication, the impacts are shown in Fig. 3. For human toxicity, terrestrial and freshwater ecotoxicity, the impacts are shown in Fig. 4. The contribution to the total impact was divided into collection and transportation (C&T), avoided products, construction, emissions, and operation. The net value of the impact represents the sum of positive and negative contributions. C&T refers to impacts (direct emissions during transport, indirect emissions due to road and truck construction) due to collection and transportation of PET waste, rejected PET waste, waste materials generated during PET waste disposal/recycling (leachate, slags), and recycled PET bales from sorting cooperatives to recycling facility. Avoided products refers to electricity generated during incineration of PET waste and the recycled PET, as appropriate for each scenario. Construction refers to impacts of building the facilities, such as building machinery fuel use and direct emissions, and impacts for manufacturing and transporting construction materials. Emissions include the direct emissions from the waste treatment (or recycling) options. Operation includes the impacts due to energy and material use in each scenario. Impacts for scenarios S8 and S9 are not shown in the figures, since they only differ from S5 for C&T, and the difference in the net impact was not significant. Table S4 in the Data in Brief article (Martin et al., 2020) shows the values of the impacts (including the breakdown of contributions) in all categories for all scenarios.

Scenario 5 presented the lowest net impacts for all categories considered. In fact, the net impacts were all negative for this scenario. The scenario where all PET waste is incinerated (S7) presented the highest net impact values in all categories, except in the ozone depletion and freshwater eutrophication categories. In these two categories, S6, the scenario where all PET waste is landfilled, had the highest impacts. Scenarios 1, 2, and 4 are weighted-average combinations of scenarios 5, 6 and 7. In particular, S1 is 3.6% S5 and 96.4% S6; S2 is 50% S5 and 50% S6; S4 is 50% S6 and 50% S7. Scenario 3 is a combination of S5 and S7, with the rejected PET in S5 being incinerated, instead of landfilled. For conciseness, the results and discussion will focus on scenarios 5, 6 and 7.

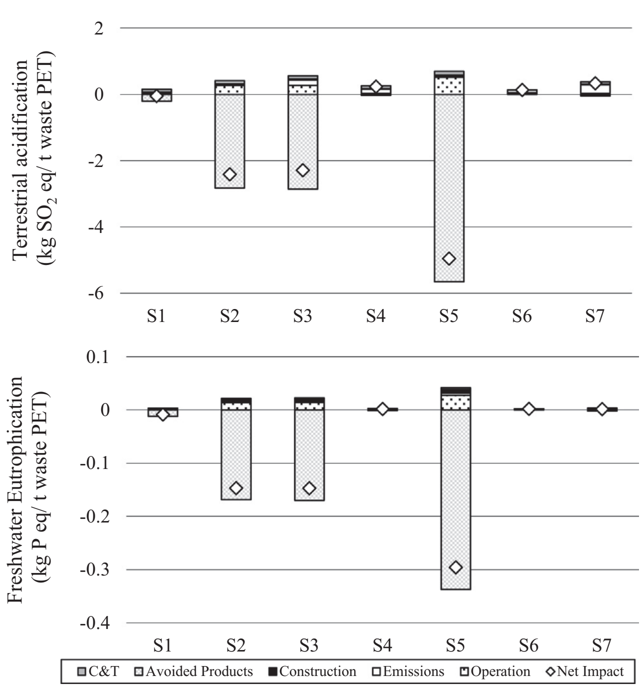

Fig. 3. Total impact for terrestrial acidification and freshwater eutrophication categories and breakdown of contributions.

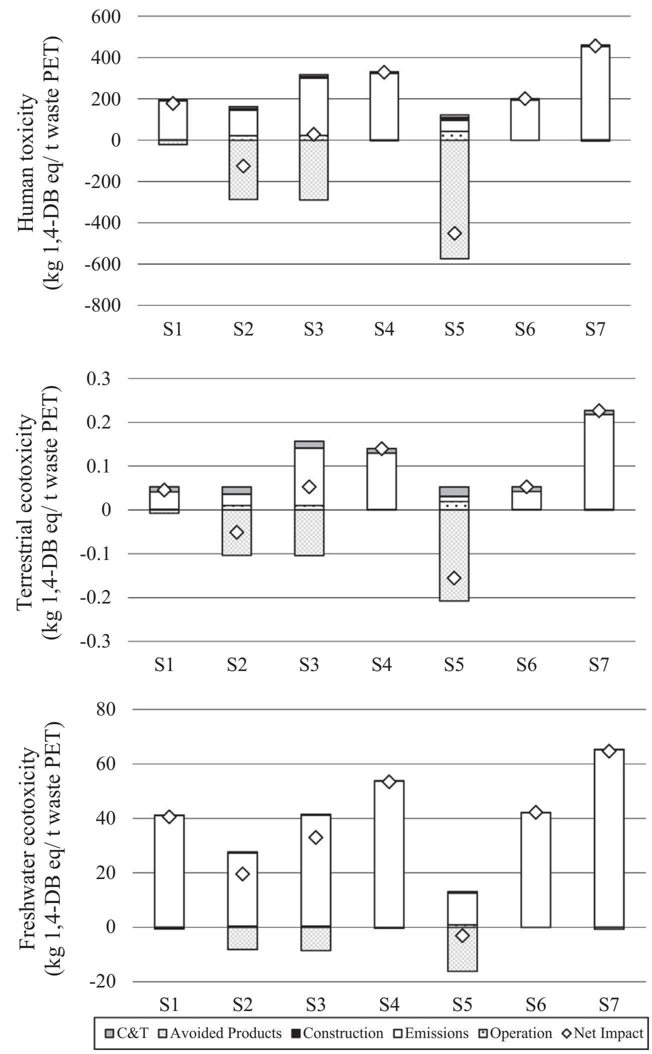

Fig. 4. Total impact for human toxicity, terrestrial and freshwater ecotoxicities categories and breakdown of contributions.

For the climate change category, the major overall contributor for S5 was avoided products. On the burden side, the main contributors were operation (52%), C&T (31%), and emissions (13%). For S6 there were only burdens, with emissions (67%) and C&T (26%) being the main ones. For S7, the main contributor was emissions, which accounted for 98% of all the burdens. There was a small offset (3% of the total burden) due to avoided products. It should be noted that, for S1, the net impact was only 45% of the net impact of S6.

Regarding ozone depletion, there were no contributions from direct emissions to the total impact in all scenarios. In general, the main contributors were operation and C&T, on the burden side (positive impact values), and avoided products on the benefit side (negative impact values). For S6 and S7, C&T was the major burden (70% and 85% of the total burden, respectively). For S5, operation was the major burden (82%). All scenarios proposed (except S6) had smaller net impacts on ozone depletion than the base scenario (S1). However, larger reductions were obtained when recycling was considered than when incineration was considered.

Regarding the terrestrial acidification category, for S5 the avoided products were 8 times larger than the total burden. The main contributors on the burden side were operation (74%) and C&T (16%). For S6, the main contributors were C&T (63%) and operation (25%). For S7, emissions (69%) were the most contributing burden. In the freshwater eutrophication category, the avoided product for S5 was also very significant, and operation (66%) and construction (16%) were the main burdens. The burdens for S6 and S7 were very small, being one order of magnitude smaller than the burdens for S5. The net impacts for S1 were negative for the terrestrial acidification and freshwater eutrophication categories.

For human toxicity, emissions were the main burden for S5, S6 and S7, representing 43%, 96%, and 98% of the total burden, respectively. For S5, operation was another significant burden (35%), and avoided products were 4.7 times larger than the total burden. For terrestrial and freshwater ecotoxicity, the main burden was from emissions for all scenarios, with the exception of S5 in the terrestrial ecotoxicity category. For this particular case, C&T and operation were the main burdens. The avoided products for the scenarios with recycling provided larger offsets for terrestrial ecotoxicity than for freshwater ecotoxicity.

5. Discussion

Some observations and trends are common for all impact categories. For C&T, recycling presented higher impact than landfilling and incineration, due to long transportation distances of the bales from the sorting cooperatives in Bauru to recycling industries in other cities. For incineration, the avoided product was electricity, assumed to be produced in hydroelectric plants. Hydroelectric energy has less impacts in most categories considered than traditional power plants, resulting in small offsets. Furthermore, the contribution of the operation phase for incineration was negligible because the heat used in the incineration facility was assumed to be generated by the combustion of PET waste, so that no external supply was necessary.

5.1. Climate change

Emissions were such a considerable burden for S7 in the climate change category because nearly all carbon in PET is oxidized and released to the atmosphere during incineration. During landfilling of PET waste, due to its low degradability, only 1–2% of the carbon is released in 100 years (Sundqvist, 1999). The air emissions inventory used in the present study assumed a default value of 1% for PET degradability in landfills (Doka, 2007). For mechanical recycling, the molecular structure of PET does not change, so there are no carbon emissions. In all scenarios where PET recycling is considered, the PET rejected by the sorting cooperatives and by the recycling industry is either landfilled or incinerated, and any contributions from direct emissions to the climate change category stems from either of these two options.

Comparing S5 and S6, when recycling of PET waste occurs (S5), the burdens due to operation, construction, and C&T increased 18.3, 2.9, and 1.9 times, respectively, compared to landfilling of PET waste (S6). For operation and construction, this increase is due to greater electricity use and larger infrastructure needed during PET sorting and recycling. For C&T, the increase is due to the transport of bales from Bauru to recycling companies in other cities. Even though the burdens increased, the net impact decreased due to the large offset (-1580 kg CO_2 eq./t waste PET) provided by the avoided product, replaced fossil-based PET. The impact on climate change from fossil-based PET production is a result of CO_2 and CH_4 emissions during raw materials manufacturing, in particular, xylene for terephthalic acid production. By replacing this product with recycled PET, these burdens are avoided. The offset provided by incineration (-69 kg CO_2 eq./t waste PET) was comparatively much smaller.

Considering S1, even a small amount of recycling was able to significantly improve the impacts on climate change, resulting in a net impact of 46 kg CO_2 eq./ t PET waste. In comparison, scenario 6, which considered 100% landfilling, had a net impact of 101 kg CO_2 eq./ t PET waste. For the other scenarios, a mix of PET recycling and incineration (S3) resulted in a higher net impact than the current scenario (S1), while a mix of PET recycling and landfilling (S2) presented a lower net impact than S1. Therefore, if achieving high recycling rates is not possible, it would be better to landfill the PET waste than to incinerate it.

5.2. Ozone depletion

Depletion of the ozone layer is caused by the release of halogenated hydrocarbons, and since these substances are not emitted during the treatment of PET waste, none of the scenarios resulted in any burden from direct emissions for this category. For S5, the large contribution (82% of total burden) from the operation phase occurs due to the production of NaOH, which is used in the PET cleaning process in recycling facilities. The impact caused by C&T on ozone depletion comes from the production of fossil fuels used in transportation trucks. The large offset provided by recycling PET (S5) comes from avoided fossil-based PET production, which releases CFCs compounds during the petroleum refinery process.

5.3. Terrestrial acidification and freshwater eutrophication

Terrestrial acidification is related to the emission of substances, usually containing N and S, which decrease the pH of the soil upon deposition, impacting plant biodiversity (Roy et al., 2012). Regarding the burdens, recycling (S5) presented higher impacts than landfilling (S6) and incineration (S7), specially for the operation phase. For this phase, 90% of the impacts came from operation in the recycling industries, which includes heat utilization and washing chemicals (NaOH, H_2SO_4). Incineration (S7) presented higher burdens than landfilling (S6) due to direct emissions of NO_x and SO_2, which are 0.46 kg and 1.57×10^{-3} kg, respectively, per t of PET waste incinerated (Doka, 2013). These emission values are much smaller for a landfill: 1.45×10^{-3} kg NO_x and 1.93×10^{-4} kg SO_2 per t PET waste landfilled (Doka, 2007). The production process of fossil-based PET has significant acidification impacts (11.5 kg SO_2 eq per t PET produced), most of which (92%) comes from the production of the raw materials used in the production of PET (EG and TPA), which explains the large offsets provided by the avoided products in the scenarios that consider PET recycling.

Freshwater eutrophication is caused by nutrient (mainly P and N) accumulation in water bodies, causing excessive algal growth and consequently anoxic conditions in the water (Pretty et al., 2003). The trends observed were similar to those discussed for acidification. However, the large offset obtained from PET recycling came from avoided emissions of phosphate (PO_4^{3-}) during treatment of residues from fossil-based PET production. There were negligible freshwater eutrophication impacts from emissions during PET incineration because the ReCiPe method does not have impact factors for N-containing substances (such as NO_x, which is emitted during incineration) to air for this category. For PET landfilling, there were also negligible impacts for eutrophication because the leachate produced is treated, and land application of the compost generated during leachate treatment was not considered.

5.4. Human toxicity and ecotoxicity

The large contribution of emissions to the toxicity impacts for the incineration scenario (S7) were due to release of toxic substances, mainly vanadium, titanium, and antimony. These metals are present in the catalysts used in the de-NO_x unit and also in trace amounts in the PET waste. For landfilling (S6), the toxicity impacts stemmed from direct emissions to water of substances, such as Mn, Pb, Ba, Cu, Zn, and Hg during leachate treatment in the WWTP. PET has negligible water content, so it does not generate significant quantities of leachate. However, PET is landfilled with other wastes that do generate leachate, and small amounts of impurities present in PET (such as Na, V, Ti, Cl, Sb, Zn, Mn, Cu, and Ni) can leach into the leachate. The inventory utilized for landfilling of PET waste assumed an average leachate quantity, but corrected the composition of this leachate to be waste-specific (Doka, 2007).

For the scenarios where recycling occurs, the burdens for human toxicity and freshwater ecotoxicity were mostly due to emissions. These burdens came from the landfilling of the rejected PET waste. The sorting and recycling processes do not have direct emissions; however, their operation contributed to human toxicity and terrestrial ecotoxicity. In these cases, the burdens were related to energy use in the recycling industries, and production of cleaning substances, such as NaOH and soap. C&T was another major burden for terrestrial ecotoxicity due to heavy metal emissions to air and soil during tire abrasion and brake wear. The offset provided by PET recycling was due to avoided emissions from treatment of residues from fossil-based PET production. For human toxicity, the main avoided emission was of manganese to water. For terrestrial ecotoxicity, it was Zn and Cu to soil, while for freshwater ecotoxicity, it was Cu to water.

6. Conclusions

The recycling scenarios outperformed the incineration scenarios in all impact categories analyzed, indicating that recycling could be a better option than incineration, from an environmental standpoint, for the city of Bauru. Landfilling was less impactful than incineration for all categories, expect for ozone depletion and freshwater eutrophication, although the net impact values were close for both categories. Environmental impacts also decreased as the recycling capacity increased, when landfilling of the remaining PET waste was maintained. Thus, recycling appears to be the best option. However, the recycling rate in the city is very low due to lack of a waste-sorting culture, which would greatly hinder the recyclables collection process, and the fact that, under the current legislation, recycling cooperatives cannot be managed by private-sector companies; they must be managed by collector's associations, which usually lack monetary resources to rapidly expand and keep up the production capacity. This study can bring to the attention of policy-makers and regulators the need to allow private sorting services or to provide more funding and training to the cooperatives, as well as educating the population as to the importance of source separation.

This work did not consider the amount of PET waste collected informally by waste pickers due to the lack of official information and data for the city of Bauru. It is suggested that future works attempt to estimate the volume and destination of the PET waste collected in this manner in Bauru.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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