Waste Management 126 (2021) 781–790

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Post-consumer plastic packaging waste flow analysis for Brazil: The challenges moving towards a circular economy

Isabella Pimentel Pincelli [a], Armando Borges de Castilhos Júnior [a,*], Marcelo Seleme Matias [a], Emília Wanda Rutkowski [b]

[a] Department of Sanitation and Environmental Engineering, Federal University of Santa Catarina (Universidade Federal de Santa Catarina), Florianópolis, Brazil
[b] FLUXUS lab [INFRA/FEC], State University of Campinas (Unicamp), Campinas, Brazil

ARTICLE INFO

Article history:
Received 7 September 2020
Revised 8 February 2021
Accepted 1 April 2021
Available online 21 April 2021

Keywords:
Post-consumer plastic packaging
Material flow analysis
Resource management
Waste management
Circular economy

ABSTRACT

Plastic packaging has been used increasingly worldwide in a broad range of application. Plastic packaging has a short lifetime, which generates a large amount of waste. However, robust information on plastic packaging waste flow is generally not available, especially for developing countries such as Brazil. We analyzed and quantified Brazilian post-consumer plastic packaging waste (PPW) flows using material flow analysis (MFA) for the year 2017. The system modeled covered from the manufacturing stage of plastic packaging up to its waste management stage. We used a range of data sources, whose quality we assessed using uncertainty characterization. The results showed that Brazil generated 12 Mt of PPW in 2017, and the management of 63% of that was not monitored. The majority of monitored PPW was disposed of into landfills, but 0.8 Mt of PPW was improperly disposed. Informal collection was 24% greater than formally managed selective collection. Only 4.5% of the PPW generated in Brazil was recycled. The results identified the major national challenges in relation to PPW management as being that information systems needed to be improved, informal waste collectors needed to be socially and productively included in the management systems, and recovery systems needed to be developed towards a circular economy.

1. Introduction

Large-scale production and use of plastic have increased exponentially since the 1950s (Geyer et al., 2017). Geyer et al. (2017) estimated that 8,300 Mt of plastics were produced worldwide from 1950 to 2015. The packaging industry is the sector that consumes most plastic polymers; in 2015, 40% of plastic polymers worldwide were used for packaging production (Groh et al., 2019). As a result, plastic waste generation has grown worldwide. In 1960, the plastic share in municipal solid waste (MSW) in high- and middle-income countries was less than 1% and it rose to over 10% by 2005 (Jambeck et al., 2015).

Plastic waste is of particular concern, as the scientific community has reported several adverse effects on human health and on the environment caused by plastics. Moreover, plastic pollution in marine and freshwater environments has emerged as a global issue (Eerkes-Medrano et al., 2015). Hence, proper management of plastic waste could contribute to reducing its environmental impacts (Eygen et al., 2017).

In high-income countries, plastic recycling has increased due to legislative and economic instruments (UNEP, 2015). Indeed, in 2015, the European Union adopted an action plan for a circular economy in which prioritize strategies for managing plastic packaging (European Commission, 2018). However, until 2015, only 9% of all plastics ever made worldwide were recycled (Geyer et al., 2017).

In developing countries, in particular, recycling rates are far below their potential. In Brazil, according to the National Sanitation Information System (SNIS, in Portuguese) (SNIS, 2019a), only 1.65% of the MSW collected in 2017 was recovered through recycling. The Brazilian National Policy on Solid Waste (PNRS, in Portuguese) of 2010 established that all recyclable solid waste should be recovered and only non-recyclable solid waste could be disposed of in landfills (PNRS, 2010). The PNRS established the principle of shared responsibility on waste management among supply chain actors (Guarnieri et al., 2020). The policy obliged manufacturers, importers, distributors, and traders of several types of products to implement reverse logistics (Ribeiro and

* Corresponding author at: Departamento de Engenharia Sanitária e Ambiental, Universidade Federal de Santa Catarina, Florianópolis, SC CEP 88.040-900, Brazil.
E-mail address: armando.borges@ufsc.br (A. Borges de Castilhos Júnior).

https://doi.org/10.1016/j.wasman.2021.04.005
0956-053X/

Kruglianskas, 2020), including plastic packaging. Thus, the government established a Packaging Sector Agreement to promote the packaging reverse logistic as an instrument of the PNRS (2010).

Furthermore, informal waste collectors, called ''waste pickers'', are responsible for most of the recycling in low-income countries, achieving recycling rates of 20% to 30% for MSW (UNEP, 2015). Therefore, MSW management in Brazil is a complex task because, in addition to economic and environmental aspects, there is also the socio-economic aspect represented by the waste pickers' work within the collection, classification and commercialization of recyclable waste (Fidelis et al., 2020), such as post-consumer packaging plastic waste (PPW). Federal Government and some State Governments during the first decade of this century promoted the socioproductive inclusion of waste pickers, by enforcing legislation and financing socio-economic inclusive programs for waste pickers. Even tough, society tends to neglect these professionals.

Material flow analysis (MFA) is a relevant tool for plastic waste management analysis, since it provides a systematic assessment of the state of and changes in material flows within a system defined in space and time (Brunner and Rechberger, 2004). Allesch et al. (2015) reviewed the application of MFA in waste management and their results showed that MFA is instrumental in understanding how waste management systems work. Thus, several studies on MFAs for solid waste and for plastics products have been conducted for developed countries (Bogucka et al., 2008; Brouwer et al., 2018; Deshpande et al., 2020; Eygen et al., 2017; Eygen et al., 2018; Kawecki et al., 2018).

Despite its relevance, MFA has not been widely applied in low- and middle-income countries. Applying MFA in developing countries can be challenging due to limited data (Millette et al., 2019). However, Vilaysouk et al. (2019) measured material inputs and outflows of waste and emissions for Laos. Kabera et al. (2019) realized a mass-flow diagram of MSW for Kigali in Rwanda, and Makarichi et al. (2018) performed an MFA on solid waste for Zimbabwe. Millette et al. (2019) conducted an MFA of plastics for Trinidad and Tobago. Performing MFAs using currently available data could also support the development of a circular economy within a developing country (Millette et al., 2019).

In Brazil, a key consideration for managers and researchers when analyzing MSW systems is data availability, because information is lacking (Ibáñez-Foréz et al., 2018). Even so, plastic waste management has been studied already for Brazil. Pacheco et al. (2012) measured the plastic recycling capacity of Rio de Janeiro. Rutkowski and Rutkowski (2017) analyzed Brazilian recycling chains for plastics by visiting waste pickers' associations. Coelho et al. (2011) analyzed logistics models for post-consumer PET recycling for Brazil. Oliveira et al. (2019) investigated the supply chain and reverse channels of polystyrene (EPS) packaging in Brazil and pointed to the main challenges facing a move towards a circular economy. However, MFA has not yet been used for analyzing PPW flows in Brazil.

Therefore, the question that the present study aims to answer is "What was the PPW management flow system like in Brazil, in 2017, and what barriers and opportunities are there to improving it?" Further to that, we ask "What role did the informal waste sector play?" The study aims to analyze the challenges the country would face in reaching a more circular production of PPW considering the socioproductive inclusion of waste pickers. This study is the first MFA for PPW in Brazil and provides an estimate of previously unknown flows: the informal collection of PPW, the PPW tailing in sorting units, and the non-monitored management of PPW.

2. Method

A static MFA of PPW was realized for Brazil in 2017 to analyze the PPW management in the country. We identified and synthetized disperse data on PPW management in Brazil. Firstly, we collected information from existing databases, then, we compiled the information to represent the input values of the flows. The MFA was performed by balancing the system and calculating the flows' output values.

2.1. System description

The MFA studied PPW, which is MSW; industrial waste was not considered and PPW polymeric composition was not analyzed.

Plastic product chains comprise three main stages — the production, consumption, and waste management (Eygen et al., 2017). The qualitative model of PPW management in Brazil is presented in Support Information S1.

In the production stage, plastic packaging is manufactured; the MFA system does not consider the primary production of plastics. Further on, plastic packaging is sold by the manufacturing industry for consumption. In addition, Brazilian imports and exports of plastic packaging are regarded as plastic packaging delivered for consumption.

After plastic packaging is used, it is discharged as MSW and referred to as PPW. In Brazil, MSW covers urban cleaning waste, household waste, and commercial solid waste similar to household waste in nature, composition, and volume (PNRS, 2010). In Brazil, irregular disposal of MSW is a main concern (IPEA, 2012). Thus, we counted a PPW flow that its management is not monitored, so the flow represents the material that is managed but not monitored and the mismanaged material, that could have leaked out of the system.

The Brazilian PPW collection system was observed in terms of three main categories — mixed collection, selective collection, and informal collection.

Mixed collection is unsorted MSW sent for disposal (Cunha and Caixeta Filho, 2002) as general waste in landfills, controlled dumpsites, or dumpsites (SNIS, 2019a). While landfill is technically designed and monitored, dumpsites are not. The controlled dumpsites receive a layer of soil (Guimarães et al., 2019). The mixed collection of PPW is undertaken by public agencies, private agencies, and other agents such as philanthropic entities and large solid waste generators (SNIS, 2019a).

Selective collection is only of dry recyclable waste. Selective collection in Brazil is undertaken by public agencies, private agencies, and waste pickers associations or cooperatives with formal agreement or contract with municipalities (SNIS, 2019a).

Informal collection is the non-regulated activity of extraction of recyclable materials, such as PPW, from mixed MSW (Ezeah et al., 2013) or segregated material that is given directly to waste pickers without municipalities control. The informal sector recycling network is composed of household waste collectors, street pickers, itinerant waste buyers, MSW collection crews, dumpsite pickers, intermediate dealers (Ezeah et al., 2013) and waste pickers association or cooperatives.

Collected PPW is transported to sorting units, for sorting, pressing, baling, and trading of recyclable waste to recycling centers (Campos, 2014; SNIS, 2019a). A variable percentage of PPW is unfitted for recycling and discharged as tailing. Some PPW is recycled for the manufacture of new packaging and some is recycled for non-packaging applications (Brouwer et al., 2018).

Incineration was not examined because this technology is not used for MSW treatment in Brazil (Lima et al, 2018; SNIS, 2019a).

2.2. Data collection and compilation

We collected data on PPW management in Brazil from existing data sources, mostly official Brazilian government databases. A description of the data sources is presented in Table S2.1 and a summary of all data utilized for each input flow is provided in Table S2.2 (Support Information S2), however, we did not have previously information about the informal collection of PPW, the PPW tailing sorting units, and the non-monitored management of PPW (Table S2.3). As specific data on PPW are scarce in Brazil, we combined information for estimating MFA input flows. Support Information S7 summarizes the data sources and data compilation for all the input flows.

The data on plastic packaging mass production and industrial sales in 2017 were taken from the annual industrial survey of the Brazilian Institute of Geography and Statistics (IBGE) (IBGE, 2017a,b). The masses compositions of plastic packaging manufacturing and industrial sales are presented in Fig. 1. More information about plastic packaging categories manufactured and sold industrially is presented in Support information S3.

Data on importing and exporting plastic packaging were extracted from the Brazilian Ministry of Economy Industry, Foreign Trade and Services (MDIC, 2017) database.

Calculation procedures were needed for estimating the following input flows: the generation of PPW; the selective collection of PPW; and the mixed collection of PPW.

The estimation of the generation of PPW was based on Geyer et al. (2017) procedure by combining plastic packaging production data with plastic packaging lifetime. Additionally, the amount of plastic packaging imported and exported was considered. The lifetime of plastic packaging is estimated as 1 year (Ciacci et al., 2017; Kuczenski and Geyer, 2010; Patel et al., 1998) and its mean lifetime is 0.5 year (Geyer et al., 2017). Thus, we estimated that half of the plastic packaging that became waste in 2017 was manufactured in 2016 and half in 2017. That formula is shown in (1), in which *PPW* denotes the mass (t) of plastic packaging waste generated, P denotes the mass (t) of plastic packaging produced, and I and E, the mass (t) of plastic packaging imported and exported. The results of the input flow of PPW generation are presented in Support Information S4.

$$PPW_{(2017)} = 0.5(P_{(2017)} + P_{(2016)} + I_{(2017)} + I_{(2016)} - E_{(2017)} - E_{(2016)}) \quad (1)$$

To establish the amount of PPW collected by selective and mixed collection, we firstly estimated the MSW collected by selective and mixed collection, followed by the proportion of plastic packaging in the MSW.

For MSW collection information, data were taken from the SNIS (2019b). The SNIS research is the only national research on solid waste with available dataset for the 2017 year. However, municipalities' participation in the survey is voluntary and not all of them participated (SNIS, 2019a). Therefore, information on MSW management for the unreported municipalities was estimated.

Brazilian databases present the total amount of MSW collected in Brazil, which includes that from selective collection. Therefore, data about MSW collected by mixed collection were extracted from the SNIS (2017b) database by deducting the amount collected selectively by each agent for each municipality. In this way, data on mixed MSW collected masses were compiled for 60% of the Brazilian municipalities. A multiple linear regression analysis was performed to project the MSW collected by mixed collection for the unreported municipalities. The general expression of multiple regression is shown in Formula (2) below, in which y denotes the predicted variable, a denotes a constant, b denotes the regression coefficients, and $\times$ denotes the independent variables. Municipal urban population (IBGE, 2017a,b) and municipal GDP were used as independent variables (IBGE, 2016).

$$y = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n \quad (2)$$

The SNIS dataset (2019b) was used to extract information on the amount of MSW collected by each of the mixed collection agents. We collected information on the amount of MSW deposited in landfill, dumpsites, and controlled dumpsites from the SNIS report (SNIS, 2019a).

Information about municipalities running selective collection services was extracted from SNIS (2019b) and IBGE (2011). A total of 63.8% of the Brazilian municipalities informed SNIS whether they run selective collection services. The information for the others 36,2% was collected from IBGE (2011), although related to 2010, it allowed a Brazilian overview. A total of 1771 municipalities were provided, in 2017, with official selective collection, representing 33% of Brazilian municipalities and 63% of population.

The SNIS (2019b) provided data on the selective collection mass of MSW for 70% of the Brazilian municipalities identified with selective collection services. A multiple linear regression analysis was used to project the selectively collected MSW masses for the

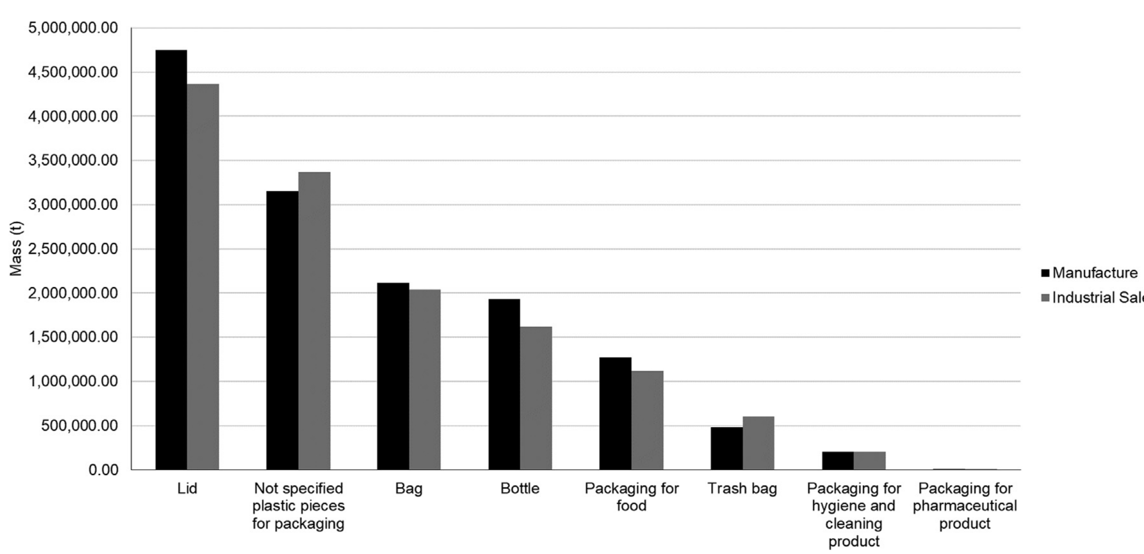

Fig. 1. Plastic packaging produced and sold by industries in Brazil in 2017 (IBGE, 2017a,b).

unreported municipalities on the SNIS database. Municipal gross domestic product (GDP) (IBGE, 2016) and the human development index (HDI) (UNDP, 2010) were used as independent variables for projecting selective collection masses.

The SNIS (2017a) report presented a proportional rate of MSW selectively collected by public agencies, private agencies, and formal waste picker organizations. Thus, we determined transfer coefficients for each agency who undertook the selective collection by extracting their respective rate information from the SNIS (2017a) report.

After calculating the masses of MSW collections, we estimated the proportion of plastic packaging in the MSW. For the proportion of plastic from selective collection, the SNIS (2019a) information was taken from 2017 as published in its report. For the proportion of plastic from mixed collection, information was taken from IPEA (2012) study, which is the only national research on Brazilian MSW composition. The proportion of plastic waste that is packaging in selective and mixed collections was expressed by Geyer et al.'s (2017) worldwide estimate, because there are no Brazilian studies about the levels of PPW in MSW.

Finally, the mass of PPW which was recycled was obtained from the Technical Report of the Brazilian Sectoral Agreement for the implementation of reverse logistics of general packaging (SINIR, 2017).

Data on manufacturing new products by recycling PPW was extracted from the Brazilian PET Industry Association (ABIPET, 2016) report, which referred to PET products. The report presents the breakdown of final uses of recycled PET in Brazil in 2016. The rates of PPW recycled for new plastic packaging and for non-packaging applications were extracted from this report and used as a transfer coefficient in the MFA system.

2.3. Data quality

Data availability to quantify material flows is often limited, owing to data scarcity or missing data (Laner et al., 2016). Data used for MFA are interdisciplinary, have heterogeneous sources, and may vary on formats and qualities (Schwab et al., 2017). Therefore, assessing the reliability of the flows provides the quantification of the data limitations for system understanding.

The quality of the data sources was assessed using the uncertainty characterization method developed by Laner et al. (2016). The approach was developed to include data quality indicators within the pedigree matrix presented by Weidema and Wesnæs (1996), combined with the quantification of uncertainty based on data source classification as proposed by Hedbrant and Sörme (2001). Firstly, data quality of all MFA input flows was evaluated by data quality indicator scores (Sieber et al., 2020), presented in Support Information S8. These indicators encompass the geographical and temporal representativeness, the investigated material, and the completeness and reliability of the source (Sieber et al., 2020). The assigned scores for each information source are presented in Support Information S10.

These various data quality indicators were translated into uncertainty by coefficients of variation (CVs) (Muchangos et al., 2019). Uncertainty was assumed to increase exponentially with poor data quality (Laner et al., 2016). Data uncertainty was assumed to be normally distributed, because of its mathematical convenience (Tran et al., 2018). These assumptions have also been made by Muchangos et al. (2019), Eygen et al. (2018), Tran et al. (2018), Makarichi et al. (2018), and Warrings and Fellner (2018) while executing Laner et al. (2016) approach. The CVs are the standard deviation divided by the mean (Eygen et al., 2017). The detailed procedure for the CV calculation is shown in the Support Information S9.

2.4. MFa

The input flows that we used to perform the MFA are summarized in Support Information S7. We used the previously calculated CVs as input uncertainty values for the input flows (Support Information S11).

MFA is based on the law of conservation of matter within the system and all its processes (Brunner and Rechberger, 2004). The flows are calculated by using a material balance to compare the mass of all flows entering, leaving, and stocked at a process (Eygen et al 2017). Therefore, the mass of all flows entering a process must equal the mass of flows leaving this process plus the stock change (Allesch et al., 2017). Support Information S12 presents the mass balance equations. Using this procedure, unknown flows can be calculated by balancing the system (Eygen et al., 2017). Therefore, the previously unknown flows of the system — the informal collection of PPW, the PPW tailing in sorting units, and the amount of non-monitored PPW— were estimated by the MFA (Table S2.3).

We used STAN 2.6 software, developed by Tu Wien, to perform the MFA and for data visualization through a Sankey diagram, in which the thickness of the flows was proportional to their value (Cencic and Rechberger, 2008). We used STAN to reconcile data and to perform error propagation. STAN is a free software that has been used widely in the scientific literature for several MFAs, such as the studies performed by Boh and Clark (2020), Tazi et al. (2019) and Brouwer et al. (2018).

Input redundant information are used to reconcile the MFA input data (Cencic and Rechberger, 2008). The method of least squares is used for data reconciliation, in which uncertainties are used as weighing factors (Cencic, 2016). By data reconciliation, we calculated the values for the MFA output flows – with previous information. Subsequentially, the reconciled values were used to calculate previously unknown flows (Cencic and Rechberger, 2008) by balancing the system.

STAN presents a data reconciliation quality (DRQ) indicator (Brouwer et al., 2018), which expresses the difference between 1 and the mean value of measurement adjustments per maximum allowed adjustment. DQR ranges from 0 to 1 (Cencic, 2016), and DQR close to 1 indicates that the reconciled data matched the original data well (Brouwer et al., 2018).

3. Results and discussion

Firstly, we present the results for the projections of the selective and mixed collections of MSW. Subsequently, we show the input data quality uncertainty of the MFA input flows. Finally, we display the PPW modeled system and the values of the outputs flows.

3.1. MSW collections projections

There were 1,771 municipalities served by a selective collection service in Brazil, accounting for 32% of all Brazilian municipalities. The SNIS (2019b) database lacked information on selective collection mass for 536 of these municipalities, which had their mass estimated by linear regression. The multiple linear regression equation, established to predict the mass of selectively collected MSW in Brazil in 2017, is shown in Formula (3), in which *SCM* is the selective collection mass (t). This regression model explains 36% of the original variability (Table S5.1). The regression residuals follow the normal distribution (Figure S5.1 and Figure S5.2).

$$SCM = 10^{(-1.18+0.57 log_{10} GPD - 0.81 log_{10}(1-HDI))} \quad (3)$$

By projecting the selective collection mass for the unreported municipalities in the SNIS (2019b) database, the mass of selectively collected MSW in Brazil in 2017 was estimated as 1.87 Mt (Table 1).

The analysis of the SNIS (2019b) dataset revealed the MSW mass collected by mixed collection in 2017 for 3,366 municipalities. The mass for the remaining 2,204 was projected by linear regression. The linear regression equation established to predict the mixed MSW collection mass is shown in Formula (4), in which *MCM* is the mixed collection mass (t). The modeled regression explains 85% of the original variation (Table S6.1) and its residuals approximate to the normal distribution (Figure S6.1 and Figure S6.2).

$$MCM = 10^{(-0.84+0.57log_{10}UP+0.11log_{10}GPD)} \tag{4}$$

The mixed collection of MSW was projected for the unreported municipalities in the (SNIS, 2019b) database. Hence, the mixed collection of MSW in Brazil in 2017 was estimated as 58.16 Mt (Table 1).

3.2. Input CVs

We present the assessment of the data quality uncertainties for the input flows in Fig. 2, which shows the CV results corresponding to the input flow. As a general trend, data uncertainties were lower for the plastic packaging production and consumption stages (F1, F2, F3 and F4), and they increased for the solid waste management stage. This trend was expected, as usually databases used for MFA are more inefficient when moving downstream in the system (Schwab et al., 2017). Detailed information on the input flows quantities and their CVs are provided in Support Information S11.

Overall, quality of information on PPW management was quite poor. Hence, Brazil needs to improve the information systems, and information should be rigorously controlled by regulatory certifications.

Complementary to improving information systems, scientific field investigations could be a valuable tool for checking the data in the field and improving information quality. On the other hand, carrying out field investigation could be challenging because Brazil has continental dimensions.

3.3. PPW flow analysis

Balancing the system and reconciling the data resulted in the MFA modeled (Fig. 3). The results present an overview of Brazilian PPW waste management, identifying its general patterns.

The system of equations was overdetermined and data were reconciled. The mixed collection of PPW flow and the final disposal flows had their data reconciled (Support Information S13). The smaller the deviation of an output flow value, after data reconciliation, from the input value, the better the consistency of the input data given the balance constraints of the model (Klingmair et al., 2016). The STAN indicator of DQR was 0.95, which indicated that the reconciled data matched the input data well, so the system modeled is consistent.

Table 1
Amount of plastic packaging collected by selective and mixed collection in Brazil in 2017 calculated as input information for the MFA.

Amount Collected (Mt)	MSW	Plastic Packaging
Selective Collection	1.87	0.27
Mixed Collection	58.16	4.24

MSW: municipal solid waste.

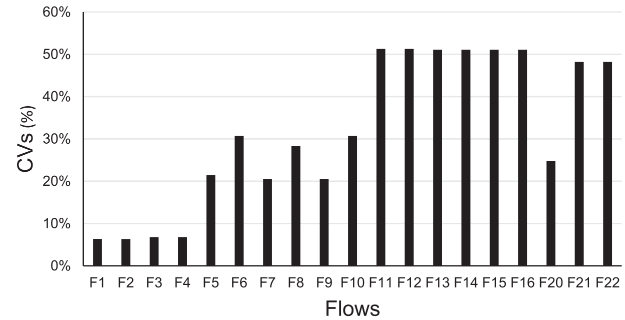

Fig. 2. Coefficients of variation for the input flows data.

The main outcome of this study was the proposed model for the PPW flows for Brazil in 2017. Information not available in the country, such as the amount of PPW informally collected, were estimated. Most of the PPW generated was not monitored. The PPW recycling rate in the country was far below its potential, and informal collection was superior to the formal selective collection.

3.3.1. Plastic packaging manufacture, sale, and consumption

Plastic packaging products consumed in 2017 were mostly manufactured within the country, around 1% was imported. A total of 13.9 Mt of plastic packaging was manufactured and 13.3 Mt was sold industrially.

In 2015, 146 Mt of plastic packaging was manufactured worldwide (Geyer et al., 2017). Our results present that 13.9 Mt of plastic packaging was manufactured in Brazil; thus, the country makes around 9% of the global production of plastic packaging.

Plastic lids and unspecified plastic pieces for packaging constitute the greatest proportion of plastic packaging mass manufactured in Brazil (Fig. 1). However, the definition of plastic packaging varies worldwide. For example, in this study, plastic trash bags and plastic bags were regarded as plastic packaging, as referred to in the Brazilian National Classification of Economic Activities (CNAE) and Mercosur Common Nomenclature (NCM). While the EPA (2019) did not consider plastic trash bags for United States PPW analysis, plastic bags were included in Brouwer et al.'s (2018) study and in the European Union's (2004) definition of plastic packaging waste. On the other hand, the data of the Ministry of Infrastructure and Water Management of The Netherlands considered plastic bags as a non-packaging object (Brouwer et al., 2018). Therefore, national databases have their own singularities when defining plastic packaging. Moreover, quantitatively comparing studies on the flows and processes of plastic packaging in other countries and time periods is difficult, as scopes regarding materials and processes may differ across the studies (Eygen et al., 2017).

3.3.2. PPW generation

Brazilian PPW generation is estimated at 12 Mt. And Brazil's per capita generation of PPW was 58 kg, similar to South Korea. Jang et al. (2020) found that South Korea was the largest per capita PPW generator, when compared to the rate in Germany, France, United Kingdom, Japan, and Belgium, thus, Brazil joined South Korea's position.

The Brazilian Packaging Sector Agreement reported that in 2017 around 8 Mt of plastic waste was generated in Brazil (SINIR, 2017), which differs from the results of the present study, which used a different procedure method. The Sector Agreement approach was based on the amount of collected solid waste, considering the plastic packaging manufacturing variation rate (SINIR, 2017). In the present study, generation was based on the amount of plastic packaging manufactured, imported, and exported, considering its

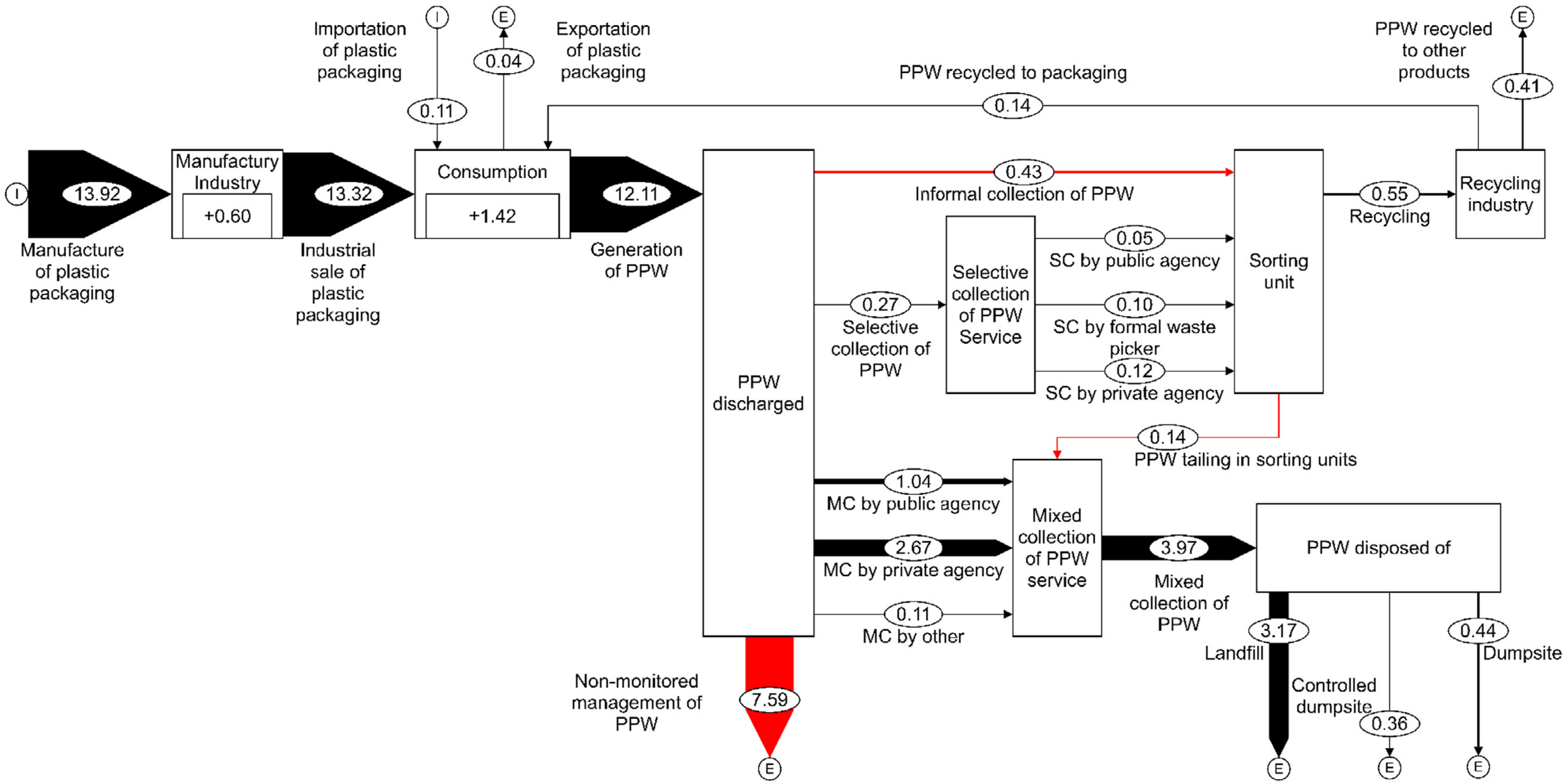

Fig. 3. Material flow analysis for post-consumer plastic packaging waste flow in Brazil for 2017 (in Mt). MC: mixed collection; SC: selective collection; The flows lacking any previous information are highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

expected lifetime. As Brazilian information systems do not monitor PPW generation, distinct approaches could lead to different results for their mass generation.

This situation was noted in other countries, comparing three studies of MFA for plastics in Austria; their results for plastic waste generated showed significant differences, which were attributed to the use of different methods and sources for data collection (Eygen et al., 2017).

3.3.3. Non-monitored PPW

The management of almost 62% of the generated PPW was not monitored. Brazil needs to improve solid waste governance and information systems. Part of the non-monitored PPW could have been mismanaged and leaked to the environment. Only 30% to 70% of solid waste generated in developing countries' urban centers is collected, and the uncollected waste may be dumped or thrown on the streets and into water bodies (Ezeah et al., 2013). The irregular discharge of PPW is a direct source of environmental pollution. According to the Ellen MacArthur Foundation, McKinsey & Company, and the World Economic Forum (2016), 32% of plastic packaging waste leaks out of the collection system worldwide; either it is not collected at all, or it is collected but mismanaged. Globally, 6.2 Mt of macro plastic was lost to the environment in 2015, and the major source of plastic loss is the mismanaged MSW in low-income and lower-middle-income countries (Ryberg et al., 2019), mainly in Africa, Latin America and the Caribbean, and the Middle East, where there is a high level of plastic consumption as well as a large proportion of inadequately managed MSW (Ryberg et al., 2018).

When PPW is transported to water bodies, plastic debris accumulates in the oceans, becoming a borderless issue. 80% of ocean plastic pollution is originated in a terrestrial environment (Walker and Xanthos, 2018). Improving plastic waste management could prevent plastic waste entering the ocean from land (Jambeck et al., 2015). Jambeck et al.'s (2015) study estimated that the Brazilian contribution to plastic waste in oceans in 2010 was up to 1 Mt. The large amount of non-monitored PPW in Brazil is alarming for unable the environmental pollution evaluation.

3.3.4. Mixed collection of PPW and disposal

Eighty-five percent of the PPW was collected by mixed collection, and disposed of in landfills, controlled dumpsites and dumpsites. Most of the mixed collection was performed by public or private agencies, and private agencies collected about 44% more than the public ones.

Mixed collection of PPW was llarger than selective and informal collection together, which presented a profile for the country still based on a linear economy. Although the PNRS regulated that recyclable solid waste, such as PPW, should be recycled (PNRS, 2010), most of the collected PPW was disposed of, mostly in landfills.

Eighty percent of the disposal of PPW was in landfills. However, about 0.8 Mt of PPW was disposed of in environmentally inappropriate sites – dumpsites or controlled dumpsites. Thus, Brazil still faces the challenge of closing its dumpsites. A few dumps have been closed, and many of them continue to operate informally (Cruvinel et al., 2019). Closed dumps are rarely recovered; most of them are land covered and abandoned (Ramos et al., 2017). Current improper waste management in Brazil causes environmental and human health impacts, through surface and groundwater contamination and air quality deterioration, contributing to climate change (Lima et al., 2018; Ramos et al., 2017).

Disposing plastic waste in landfill can contaminate soil and groundwater due to plastic leaching, therefore landfilling PPW might be considered a short-term solution (Shen et al., 2020; Teuten et al., 2009).

Globally, 12% of plastic waste was incinerated and 79% was accumulated in landfills or the natural environment between 1950 and 2015 (Geyer et al., 2017). In 2020, Austria plastic waste flow analysis showed that 67% was incinerated and 2%, landfilled (Eygen et al, 2017). In South Korea, 11% of PPW was landfilled, 38.5%, incinerated without energy recovery, and 37%, incinerated with energy recovery (Jang et al., 2020). In Brazil, so far incineration is not a viable option, there are some recent attempts to produce refuse derived fuel (RDF).

3.3.5. Selective and informal collections of PPW

Informal collection was about 24% greater than formal selective collection. Private agencies performed most of the selective collection, followed by formal waste picker organizations, and finally by public agencies.

Informal collection of PPW was higher than selective collection and demonstrated the relevance of the waste pickers' work. Other studies around the world also pointed out that the material collection rate from informal collection was higher than from formal collection (Yıldız-Geyhan et al., 2019).

Informal waste pickers' sanitation and environmental services are often not recognized (IPEA, 2012). Whereas the formal sector is modern, industrialized, and legally backed by government agencies, the informal sector lies out of state control (Ezeah et al., 2013). In Brazil, informal waste pickers are marginalized people who work collecting recyclable waste. They work in unhealthy and precarious conditions (Cruvinel et al., 2019). Informal material recovery facilities have little or no institutional control, they often do not meet legal or technical requirements or have adequate infrastructure (Campos, 2014), which contributes to an unhealthy and unsafe work environment.

Indeed, 36% of the selective collection of PPW was performed by formalized waste picker organizations, denoting their inclusion on this service.

3.3.6. PPW recovery

In sorting units, 20% of the PPW was discharged, because it was unsortable or unsorted. PPW are unsortable when it does not meet the standard quality of the recycling centers. The quality of the materials in sorting units depends on household separation (Gutberlet, 2015). Fidelis et al. (2020) noted organic waste arriving to sorting units in Brazil. The quality of the material also depends on collection, compacting trucks damage the material (Gutberlet, 2015). Furthermore, sorting processes also have capacity limitation (Gutberlet, 2015).

After the sorting process, PPW is sent to recycling factories. However, only 0.5 Mt of PPW was recycled. Thus, only about 4.5% of the generated PPW in Brazil was recycled in 2017, which showed poor material efficiency.

Recycling of PPW was quite low in Brazil in 2017. Compared with the Sectoral Agreement for Packaging estimation of the Brazilian plastic recycling rate (SINIR, 2017), the results of this study are much lower. That is because SINIR's (2017) estimation was related to the recycling of collected rather than generated solid waste.

Almost 44% of plastic packaging was recycled in Italy (Lombardi et al., 2021). In Austria, 31% of plastic waste was recycled in 2010 (Eygen et al, 2017) and in The Netherlands 30% of PPW was recycled in 2014 (Brouwer et al., 2018). South Korea recycled 13,5% of PPW in 2017. The recycling rates in The Netherlands and Austria were much higher than in Brazil. Worldwide, recycling of plastic materials is quite low, according to Geyer et al. (2017); only 9% of all plastic material ever produced has been recycled, and only 10% of that has been recycled more than once.

Recycling improve the material efficiency, most recycled PPW was used for non-packaging applications and was reinserted into other production systems. A limitation of the present study is the use of data on PET packaging (ABIPET, 2016) to portray the use of recycled PPW of all polymer types. Brouwer et al. (2018) pointed out that, in the Netherlands, most packaging manufactured from recycled PPW was PET. Indeed, the quality uncertainty for the flow of packaging made by recycled PPW was high (52%) (Fig. 2). Therefore, developing resource and solid waste management information systems could lead to more accurate flow analysis.

3.4. Challenges towards a circular economy

The analysis of PPW in Brazil revealed the challenges faced by the country to introduce a more circular productive system for the plastic packaging chain, attending to the socioproductive inclusion of waste pickers.

The circular economy could improve solid waste management by boosting developing economies through the principles of waste valorization and recycling (Ferronato et al., 2019). The implementation of a circular economy depends on redesigning the management system involving all reverse and supply chain actors (Oliveira et al., 2019). Moreover, Brazilian policies on solid waste meet the principles of a circular economy (Guarnieri et al., 2020).

The Brazilian challenges to promote circular economy are of various kinds — from improving the quality of the information system to the socio-productive inclusion of waste pickers, through an effective selective collection policy, preferably in solidarity.

The PPW information systems need to be improved, because most of the PPW generated was not monitored. Indeed, the PNRS has foreseen the National Solid Waste Management Information System (SINISA) (PNRS, 2010). The Packaging Sector Agreement forecast partnerships with the SINISA for evaluating packaging reverse logistics in the country (SINIR, 2017). Moreover, the Sector Agreement proposed a partnership with the National Association of Waste Pickers (ANCAT) for generating information on packaging waste managed by waste pickers (SINIR, 2017). Neither of these information systems has yet been implemented in Brazil, but they are expected to be installed soon (Guarnieri et al., 2020). Municipalities need to improve their administration, especially the smaller ones and the ones located in the less developed regions of Brazil (Marino et al., 2018). Furthermore, some municipalities have structural deficiencies, they do not have e-mail, internet access or computer, which complicate the circulation of information on solid waste management (Marino et al., 2018).

PPW generation originates from plastic products used on a daily basis. Therefore, a drastic change in consumption by society could reduce PPW generation, which is challenging because consumerism is highly evident across the world (Andrades et al., 2016). Nevertheless, solid waste generation could be reduced by the transition towards a circular economy, in which waste management and resource management are addressed together and products are designed to prevent waste generation.

Brazil needs to promote more effective recycling of PPW, as the present study showed a great potential for the recycling industry. Waste pickers work must be formalized and endorsed to improve the recycling. The need to integrate existing informal recycling systems into formal solid waste management was indicated in several studies (Ezeah et al., 2013; Ibáñez-Foréz et al., 2018; Yıldız-Geyhan et al., 2019). Ferronato et al. (2019) pointed out that the first strategy to introduce a circular economy within developing countries is the formalization of waste pickers. Therefore, solid waste strategies should incorporate informal waste pickers into the formal management process (Ferronato et al., 2019).

To address waste pickers' marginalization, Brazilian policies have the inclusion of waste pickers as a priority when regarding solid waste management (Fidelis et al., 2020). Thus, Brazilian policies were created for reaching sustainably towards a circular economy (Guarnieri et al., 2020) and a solidarity economy. Municipalities can contract their services without bidding process as promulgated by PNRS. The Brazilian Packaging Sector Agreement has undertaken actions to formalize waste pickers in work associations or cooperatives to drive implementation of packaging reverse logistics in the country (Guarnieri et al., 2020; SINIR, 2017). Actually, Rutkowski and Rutkowski (2015) considered Brazilian waste pickers inclusive recycling practices were among global best practice for informal sector integration.

Despite advances to address waste pickers' marginalization in Brazil, the reality has not yet fulfilled the principle; the informal sector is responsible for most PPW collection for recycling. Therefore, inclusive recycling practices still need to be expanded throughout the country. Effective investments and public awareness are needed to improve solid waste management alongside waste picker inclusion.

4. Conclusion

MFA is an approach worldwide used to assist solid waste management. Applying MFA for PPW management in Brazil for the year 2017 was challenging because of limitation of data availability. Indeed, the information data quality was assessed.

Almost two-thirds of the PPW generated was not monitored. Most of the collected PPW was disposed of, describing a linear production system. Informal collection was superior to selective collection, which shows the relevance of the waste pickers service. A relevant strategy for Brazil to move towards a circular economy is based on promoting an effective socioproductive inclusion of waste pickers. Thus, we can count on a more efficient and effective PPW recycling with a more accurate data collection. We may even be able to propose a decrease in the production of some types of plastics.

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.

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. This work was supported in part by Brazilian National Council for Scientific and Technological Development (CNPq).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2021.04.005.

References

ABIPET - Brazilian PET Industry Association, 2016. Décimo censo da Reciclagem do PET no Brasil. <http://www.abipet.org.br/index.html?method=mostrarDownloads&categoria.id=3> Accessed on the 11th November 2019.

Allesch, A., Brunner, E.P.H., 2015. Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review. J. Ind. Ecol. 19 (5), 753–764. https://doi.org/10.1111/jiec.12354.

Allesch, A., Brunner, E.P.H., 2017. Material Flow Analysis as a Tool to improve Waste Management Systems: The Case of Austria. Environ. Sci. Technol. 51, 540–551. https://doi.org/10.1021/acs.est.6b04204.

Andrades, Ryan, Martins, Agnaldo S., Fardim, Lorena M., Ferreira, Juliana S., Santos, Robson G., 2016. Origin of marine debris is related to disposable packs of ultra-processed food. Mar. Pollut. Bull. 109 (1), 192–195. https://doi.org/10.1016/j.marpolbul.2016.05.083.

Bogucka, Renata, Kosinska, Izabela, Brunner, P.H., 2008. Setting priorities in plastic waste management: lessons learned from material flow analysis in Austria and Poland. Polimery 53 (01), 055–059. https://doi.org/10.14314/polimery10.14314/polimery.2008.055.
Boh, Michael Yongha, Clark, Osborne Grant, 2020. Nitrogen and phosphorus flows in Ontario's food systems. Resour. Conserv. Recycl. 154, 104639. https://doi.org/10.1016/j.resconrec.2019.104639.
Brouwer, M.T., Van Velzen, E.U.T., Augustinus, A., Soethoudt, H., De Meester, S., Ragaert, K., 2018. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. Waste Manage. 71, 62–85. https://doi.org/10.1016/j.wasman.2017.10.034.
Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. CRC Press LLC, Boca Raton, Florida.
Campos, H.K.T., 2014. Recycling in Brazil: Challenges and prospects. Resour. Conserv. Recycl. 85, 130–138. https://doi.org/10.1016/j.resconrec.2013.10.017.
Cencic, O., Rechberger, H., 2008. Material Flow Analysis with Software Stan. J. Environ. Eng. Manage. 18, 3–7.
Cencic, O., 2016. Treatment of data uncertainties in MFA. In: Rechberger, P.H., Brunner, H. (Eds.), Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers. CRC Press - Taylor & Francis Group, Boca Raton, USA.
Ciacci, L., Passarini, F., Vassura, I., 2017. The European PVC cycle: In-use stock and flows. Resour. Conserv. Recycl. 123, 108–116. https://doi.org/10.1016/j.resconrec.2016.08.008.
Coelho, T.M., Castro, R., Gobbo, J.A., 2011. PET containers in Brazil: Opportunities and challenges of a logistics model for post-consumer waste recycling. Resour. Conserv. Recycl. 55 (3), 291–299. https://doi.org/10.1016/j.resconrec.2010.10.010.
Cruvinel, V.R.N., Zolnikov, T.R., Bashash, M., Marques, C.P.M., Scott, J.A., 2019. Waterborne diseases in waste pickers of Estrutural, Brazil, the second largest open-air dumpsite in world. Waste Manage. 99, 71–78. https://doi.org/10.1016/j.wasman.2019.08.035.
Cunha, Valeriana, Caixeta Filho, José Vicente, 2002. Gerenciamento da Coleta de Resíduos Sólidos Urbanos: Estruturação e Aplicação de Modelo Não-Linear de Programação por Metas. Gestão & Produção 9 (2), 143–161. https://doi.org/10.1590/S0104-530X2002000200004.
Deshpande, Paritosh C., Philis, Gaspard, Brattebø, Helge, Fet, Annik M., 2020. Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway. Resources, Conservat. Recycl. X 5, 100024. https://doi.org/10.1016/j.rcrx.2019.100024.
Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 75, 63–82. https://doi.org/10.1016/j.watres.2015.02.012.
Ellen Macarthur Foundation; McKinsey & Company; and World Economic Forum, 2016. The New Plastics Economy: Rethinking the Future of Plastics. < http://www.ellenmacarthurfoundation.org/publications>. Accessed on the 11th November 2019.
EPA– United States Environmental Protection Agency, 2019. Containers and Packaging: Product-Specific Data. <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/containers-and-packaging-product-specific-data#PlasticC&P>. Accessed on the 11th November 2019.
European Commission, 2018. A European Strategy for Plastics in a Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. 31p, Bruxelas. <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN&print=true>. Accessed on the 11th November 2019.
European Union, 2004. Directive, 2004/12/EC of The European Parliament and of The CouncilAmending Directive 94/62/EC on packaging and packaging waste. February 112004.
Eygen, E.V., Feketitsch, J., Laner, D., Rechberger, D., Fellner, J., 2017. Comprehensive analysis and quantification of national plastic flows: The case of Austria. Resour. Conserv. Recycl. 117, 183–194. https://doi.org/10.1016/j.resconrec.2016.10.017.
Eygen, E.V., Laner, D., Fellner, J., 2018. Circular economy of plastic packaging: Current practice and perspectives in Austria. Waste Manage. 72, 55–64. https://doi.org/10.1016/j.wasman.2017.11.040.
Ezeah, Chukwunonye, Fazakerley, Jak A., Roberts, Clive L., 2013. Emerging trends in informal sector recycling in developing and transition countries. Waste Manage. 33 (11), 2509–2519. https://doi.org/10.1016/j.wasman.2013.06.020.
Ferronato, N., Rada, E.C., Portillo, M.A.G., Cioca, L.I., Ragazzi, M., Torretta, V., 2019. Introduction of the circular economy within developing regions: A comparative analysis of advantages and opportunities for waste valorization. J. Environ. Manage. 230, 366–378. https://doi.org/10.1016/j.jenvman.2018.09.095.
Fidelis, R., Marco-Ferreira, A., Antunes, L.C., Komatsu, A.K., 2020. Socio-productive inclusion of scavengers in municipal solid waste management in Brazil: Practices, paradigms and future prospects. Resour. Conserv. Recycl. 154, i.104594. https://doi.org/10.1016/j.resconrec.2019.104594.
Geyer, Roland, Jambeck, Jenna R., Law, Kara Lavender, 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782. https://doi.org/10.1126/sciadv.1700782.
Groh, K.J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P.A., Lennquist, A., Leslie, H.A., Maffini, M., Slungef, D., Trasande, L., Warhust, A.M., Munckea, J., 2019. Overview of known plastic packaging-associated chemicals and their hazards. Sci. Total Environ. 651, 3253–3268. https://doi.org/10.1016/j.scitotenv.2018.10.015.
Guarnieri, P., Cerqueira-Streit, J.A., Batista, L.C., 2020. Reverse logistics and the sectoral agreement of packaging industry in Brazil towards a transition to circular economy. Resour. Conserv. Recycl. 153, i.104541. https://doi.org/10.1016/j.resconrec.2019.104541.
Guimarães, C.C., Barbosa, A.M., Gandolfo, O.C.B., 2019. Visual interpretation of satellite and aerial images to identify and study the evolution of inadequate urban waste disposal sites. Detritus – Multidisciplinary J. Waste Resour. Residues 6, 85–95. https://doi.org/10.31025/2611-4135/2019.13821.
Gutberlet, J., 2015. Cooperative urban mining in Brazil: Collective practices in selective household waste collection and recycling. Waste Manage. 45, 22–31. https://doi.org/10.1016/j.wasman.2015.06.023.
Hedbrant, J., Sörme, L., 2001. Data vagueness and uncertainties in urban heavy-metal data collection. Water Air Soil Pollution: Focus 1, 43–53. https://doi.org/10.1023/A:1017591718463.
Ibáñez-Foréz, V., Coutinho-Nóbrega, C., Bovea, M.D., Mello-Silva, C., Lessa-Feitosa-Virgolino, J., 2018. Influence of implementing selective collection on municipal waste management systems in developing countries: A Brazilian case study. Resour. Conserv. Recycl. 134, 100–111. https://doi.org/10.1016/j.resconrec.2017.12.027.
IPEA - Brazilian Institute of Applied Economic Research, 2012. Diagnóstico dos Resíduos Sólidos Urbanos. Brasilia, p.82. 2012. < http://repositorio.ipea.gov.br/bitstream/11058/7633/1/RP_Diagn%c3%b3stico_2013.pdf >> Accessed on the 11th November 2019.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771. https://doi.org/10.1126/science:1260352.
Jang, Y.C., Lee, G., Kwon, Y., Lim, J., Jeong, J., 2020. Recycling and management practices of plastic packaging waste towards a circular economy in South Korea. Resour. Conserv. Recycl. 158, e.104798. https://doi.org/10.1016/j.resconrec.2020.104798.
Kabera, Telesphore, Wilson, David C, Nishimwe, Honorine, 2019. Benchmarking performance of solid waste management and recycling systems in East Africa: Comparing Kigali Rwanda with other major cities. Waste Manage. Res. 37 (1_suppl), 58–72. https://doi.org/10.1177/0734242X18819752.
Kawecki, Delphine, Scheeder, P.R.W., Nowack, Bernd, 2018. Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe. Environ. Sci. Technol. 52 (17), 9874–9888. https://doi.org/10.1021/acs.est.8b0151310.1021/acs.est.8b01513.s00110.1021/acs.est.8b01513.s00210.1021/acs.est.8b01513.s003.
Klingmair, M., Zoboli, O., Laner, D., Rechberger, H., Astrup, T.F., Scheutz, C., 2016. The effect of data structure and model choices on MFA results: A comparison of phosphorus balances for Denmark and Austria. Resour. Conserv. Recycl. 109 (2016), 166–175. https://doi.org/10.1016/j.resconrec.2016.03.009.
Kuczenski, Brandon, Geyer, Roland, 2010. Material flow analysis of polyethylene terephthalate in the US, 1996–2007. Resour. Conserv. Recycl. 54 (12), 1161–1169. https://doi.org/10.1016/j.resconrec.2010.03.013.
Laner, David, Feketitsch, Julia, Rechberger, Helmut, Fellner, Johann, 2016. A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. J. Ind. Ecol. 20 (5), 1050–1063. https://doi.org/10.1111/jiec.12326.
Lima, P.M., Colvero, D.A., Gomes, A.P., Wenzel, H., Schalch, V., Cimpan, C., 2018. Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. Waste Manage. 78, 857–870. https://doi.org/10.1016/j.wasman.2018.07.007.
Lombardi, M., Rana, R., Fellner, J., 2021. Material flow analysis and sustainability of the Italian plastic packaging management. J. Cleaner Prod. 287, e.125573. https://doi.org/10.1016/j.jclepro.2020.125573.
Makarichi, L., Techato, K., Jutidamrongphan, W., 2018. Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making. Resour. Conserv. Recycl. 139, 351–365. https://doi.org/10.1016/j.resconrec.2018.07.024.
Marino, A.L., Chaves, G.L.D., Junior, J.L.S., 2018. Do Brazilian municipalities have the technical capacity to implement solid waste management at the local level?. J. Cleaner Prod. 188, 378–386. https://doi.org/10.1016/j.jclepro.2018.03.311.
Millette, Sherwyn, Williams, Eric, Hull, Clyde Eiríkur, 2019. Materials flow analysis in support of circular economy development: Plastics in Trinidad and Tobago. Resour. Conserv. Recycl. 150, 104436. https://doi.org/10.1016/j.resconrec.2019.104436.
Muchangos, L., Xue, M., Zhou, L., Kojima, N., Machimura, T., Tokai, A., 2019. Flows, stocks, and emissions of DEHP products in Japan. Sci. Total Environ. 650, 1007–1018. https://doi.org/10.1016/j.scitotenv.2018.09.077.
de Oliveira, Carla Tognato, Luna, Mônica M.M., Campos, Lucila M.S., 2019. Understanding the Brazilian expanded polystyrene supply chain and its reverse logistics towards circular economy. J. Cleaner Prod. 235, 562–573.
Pacheco, E.B.A.V., Ronchetti, L.M., Masanet, E., 2012. An overview of plastic recycling in Rio de Janeiro. Resour. Conserv. Recycl. 60, 140–146. https://doi.org/10.1016/j.resconrec.2011.12.010.
Patel, M.K., Jochem, E., Radgen, P., Worrell, E., 1998. Plastics streams in Germany—an analysis of production, consumption and waste generation. Resour. Conserv. Recycl. 24 (3-4), 191–215. https://doi.org/10.1016/S0921-3449(98)00015-9.
PNRS – Brazilian National Policy on Solid Waste, 2010. Lei n° 12.305 de 2010. Política Nacional de Resíduos Sólidos. Brasília, DF, 2010. <http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Lei/L12305.htm> Accessed on the 11th November 2019.

Ramos, N.F., Gomes, J.C., Castilhos Jr., A.B., Gourdon, R., 2017. Desenvolvimento de ferramenta para diagnóstico ambiental de lixões de resíduos sólidos urbanos no Brasil. Engenharia Sanitária Ambiental 22, 1233–1241. https://doi.org/10.1590/S1413-41522017165817.
Ribeiro, Flavio de Miranda, Kruglianskas, Isak, 2020. Critical factors for environmental regulation change management: Evidences from an extended producer responsibility case study. Journal of Cleaner Production 246 (119013). https://doi.org/10.1016/j.jclepro.2019.119013.
Rutkowski, J.E., Rutkowski, E.W., 2015. Expanding worldwide urban solid waste recycling: The Brazilian social technology in WPs inclusion. Waste Manage. Res. 33, 1084–1093. https://doi.org/10.1177/0734242X15607424.
Rutkowski, J.E., Rutkowski, E.W., 2017. Recycling in Brasil: Paper and Plastic Supply Chain. Resources 6, 43. https://doi.org/10.3390/resources6030043.
Ryberg, M., Laurent, A., Hauschild, M. Z., 2018. Mapping of global plastic value chain and plastic losses to the environment: with a particular focus on marine environment. United Nations Environment Programme. < http://wedocs.unep.org/bitstream/handle/20.500.11822/26745/mapping_plastics.pdf?sequence=1&isAllowed=y> Accessed on the 29th April 2020.
Ryberg, Morten W., Hauschild, Michael Z., Wang, Feng, Averous-Monnery, Sandra, Laurent, Alexis, 2019. Global environmental losses of plastics across their value chains. Resour. Conserv. Recycl. 151, 104459. https://doi.org/10.1016/j.resconrec.2019.104459.
Sieber, Ramona, Kawecki, Delphine, Nowack, Bernd, 2020. Dynamic probabilistic material flow analysis of rubber release from tires into the environment. Environ. Pollut. 258, 113573. https://doi.org/10.1016/j.envpol.2019.113573.
SINIR - Sistema Nacional de Informações Sobre a Gestão dos Resíduos Sólidos, 2017. Relatório Técnico Setorial de Embalagens em Geral. <http://www.sinir.gov.br/index.php/component/content/article/2-uncategorised/122-acordo-setorial-de-embalagens-em-geral>. Accessed on the 11th November 2019.
Schwab, Oliver, Zoboli, Ottavia, Rechberger, Helmut, 2017. A Data Characterization Framework for Material Flow Analysis. J. Ind. Ecol. 21 (1), 16–25. https://doi.org/10.1111/jiec.2017.21.issue-110.1111/jiec.12399.
Shen, Maocai, Huang, Wei, Chen, Ming, Song, Biao, Zeng, Guangming, Zhang, Yaxin, 2020. (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. J. Cleaner Prod. 254, 120138. https://doi.org/10.1016/j.jclepro.2020.120138.
SNIS – Brazilian National Sanitation Information System (2019a). Report: Diagnóstico do Manejo de Resíduos Sólidos Urbanos - 2017. Ministério das Cidades. Brasília, p.173. 2019. < http://www.snis.gov.br/diagnostico-residuos-solidos/diagnostico-rs-2017>
Tazi, N., Kim, J., Bouzidi, Y., Chatelet, E., Liu, G., 2019. Waste and material flow analysis in the end-of-life wind energy system. Resour. Conserv. Recycl. 145, 199–207. https://doi.org/10.1016/j.resconrec.2019.02.039.
Teuten, Emma L., Saquing, Jovita M., Knappe, Detlef R.U., Barlaz, Morton A., Jonsson, Susanne, Björn, Annika, Rowland, Steven J., Thompson, Richard C., Galloway, Tamara S., Yamashita, Rei, Ochi, Daisuke, Watanuki, Yutaka, Moore, Charles, Viet, Pham Hung, Tana, Touch Seang, Prudente, Maricar, Boonyatumanond, Ruchaya, Zakaria, Mohamad P., Akkhavong, Kongsap, Ogata, Yuko, Hirai, Hisashi, Iwasa, Satoru, Mizukawa, Kaoruko, Hagino, Yuki, Imamura, Ayako, Saha, Mahua, Takada, Hideshige, 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philos. Trans. Royal Soc. B Biolog. Sci. 364 (1526), 2027–2045. https://doi.org/10.1098/rstb.2008.0284.
Tran, H.P., Schaubroeck, T., Nguyen, D.Q., Ha, V.H., Huynh, T.H., Dewulf, J., 2018. Material flow analysis for management of waste TVs from households in urban areas of Vietnam. Resour. Conserv. Recycl. 139, 78–89. https://doi.org/10.1016/j.resconrec.2018.07.031.
United Nations Environment Programme – UNEP (2015). Global waste management outlook. International Solid Waste Association General Secretariat. Nações Unidas: Tara Cannon, 2015. < https://www.uncclearn.org/sites/default/files/inventory/unep23092015.pdf>. Accessed on the 11th November 2019.
Vilaysouk, Xaysackda, Schandl, Heinz, Murakami, Shinsuke, 2019. A Comprehensive Material Flow Account for Lao PDR to Inform Environmental and Sustainability Policy. J. Ind. Ecol. 23 (3), 649–662. https://doi.org/10.1111/jiec.2019.23.issue-310.1111/jiec.12764.
Walker, T.R., Xanthos, D., 2018. A call for Canada to move toward zero plastic waste by reducing and recycling single-use plastics. Resour. Conserv. Recycl. 133, 99–100. https://doi.org/10.1016/j.resconrec.2018.02.014.
Warrings, R., Fellner, J., 2018. Current status of circularity for aluminum from household waste in Austria. Waste Manage. 76, 217–224. https://doi.org/10.1016/j.wasman.2018.02.034.
Weidema, Bo Pedersen, Wesnæs, Marianne Suhr, 1996. Data quality management for life cycle inventories—an example of using data quality indicators. J. Cleaner Prod. 4 (3-4), 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1.
Yıldız-Geyhan, E., Yilan, G., Altun-Çiftçioğlu, G.A., Kadırgan, M.A.N., 2019. Environmental and social life cycle sustainability assessment of different packaging waste collection systems. Resour. Conserv. Recycl. 143, 119–132. https://doi.org/10.1016/j.resconrec.2018.12.028.
IBGE - Instituto Brasileiro de Geografia e Estatística, 2011. Pesquisa de Informações Básicas Municipais – MUNIC. Accessed on the 11th November 2018. <https://www.ibge.gov.br/estatisticas/sociais/educacao/10586-pesquisa-de-informacoes-basicas-municipais.html?edicao=18195&t=downloads>
IBGE - Instituto Brasileiro de Geografia e Estatística, 2017. Estimativas de população publicadas no DOU. Accessed on the 11th November 2018. <https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?edicao=16985&t=resultados>.
IBGE - Instituto Brasileiro de Geografia e Estatística, 2016. Produto Interno dos Municípios. Accessed on the 11th November 2018. https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9088-produto-interno-bruto-dos-municipios.html?=&t=downloads&utm_source=landing&utm_medium=explica&utm_campaign=pib.
IBGE - Instituto Brasileiro de Geografia e Estatística, 2017. Pesquisa Industrial Anual - Produto - PIA-Produto. Accessed on the 11th November 2018. <https://www.ibge.gov.br/estatisticas/economicas/industria/9044-pesquisa-industrial-anual-produto.html?=&t=downloads>.
MDIC - Ministério da Indústria, Comércio Exterior e Serviços, 2017. Accessed on the 11th November 2018. <http://www.mdic.gov.br/comercio-exterior/estatisticas-de-comercio-exterior/comex-vis/frame-ppi?ppi=3167>.
[dataset] SNIS - Brazilian National Sanitation Information System, 2019b. Database: Accessed on the 11th November 2018. <http://www.snis.gov.br/diagnostico-residuos-solidos/diagnostico-rs-2017>.
[dataset] UNDP - United Nations Development Programme, 2010. Atlas do Desenvolvimento Humano no Brasil. Accessed on the 11th November 2018. <http://www.atlasbrasil.org.br/2013/pt/download/>.