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REVIEW

Circular Economy and Solid Waste Management: Challenges and Opportunities in Brazil

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Abstract
Brazil has a vast territory and regional diversity, which turn the promotion of circular economy (or its improvement) into a complex challenge. This paper aims to analyse these challenges and solid waste management opportunities as a driving force for the circular economy in Brazil. Therefore, two significant challenges are discussed in this paper: increasing industrial waste recovery and improving the selective collection of municipal solid waste. Industries are concentrated in the country's South and Southeast regions, where 56% of the population live and where the best logistic infrastructure is also located. These features can help the circular economy related to industrial and municipal solid waste in those regions but bring challenges concerning the waste generated in the other part, such as the Brazilian Amazon. According to legislation, the productive sector is responsible for its products before and after use (waste prevention actions). One of the national laws establishes reverse logistic systems for several items, such as agrochemical packaging and electrical and electronic waste, but some sectors have better results than others in terms of circular economy. The cement industry in Brazil is highlighted as a case of relative success. On the other hand, the mining industry in Brazil has challenges related to the large amount of waste generated with high environmental and social risks, which caused several large accidents in the last years.

Keywords Municipal solid waste · Industry · Recycling · Reverse logistics · Amazon

Introduction

The circular economy aims, among other aspects, to minimise the environmental, social and economic damages and impacts of solid waste as well as to minimise the waste itself.

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Therefore, governments and companies can apply integrated solid waste management concepts, especially the solid waste hierarchy [1, 2].

Waste prevention is the first option in the solid waste hierarchy and may enlarge the circular economy concept by defining more precisely how to deal in case of a non-waste status of a product through a life cycle thinking [3]. Products towards waste prevention and circular economy should be designed considering dematerialisation, longevity, durability, biocompatibility, interdependency and sharing uses. This conception brings several challenges for the whole society, from industry to consumer.

When prevention does not occur, integrated solid waste management can help to reduce waste. Nevertheless, it may require a complex system of procedures and actions to decrease the amount of waste produced and increase the recovering of the waste generated, leaving the small amount possible to final disposition [4]. This search for a circular economy in solid waste management may even mean interesting business opportunities.

Developing countries, such as Brazil, usually have a lot to improve towards a circular economy and therefore towards the best solid waste management practices. Like any other country, Brazil has its particularities that can be seen as challenges and opportunities to spread circular economy practices nationwide. These challenges and opportunities exist due to the country's natural, social, economic, cultural, technological and infrastructure diversities. This paper aims to present some of the main challenges and opportunities for the circular economy in solid waste management in Brazil, observed by the authors during years of research in the field.

Brazil's primary challenge is to develop the National Policy on Solid Waste (NPSW) in its full potential. The NPSW is an advanced and comprehensive Brazilian law from 2010 about solid waste [5], but the implementation and regulation of some of its guidelines are still being structured. The law has different aspects that make the circular economy's achievement easier. It states that reusable and recyclable solid waste is an economic good with a social value that can create jobs and income and promote citizenship (Article 6).

In the present paper, some aspects of the National Policy on Solid Waste that can contribute to the circular economy in solid waste management are addressed, highlighting Brazil's problems and strengths to increase the flux of materials to be recycled.

The first part of this paper presents the integrated solid waste management (Article 10 NPSW) to solve solid waste problems considering Brazil's political, economic, environmental, cultural and social dimensions. Different issues will be addressed, as the role of waste pickers' cooperatives in this Policy (Article 8 NPSW). The Brazilian government estimates 600,000 waste pickers in the country who collect recyclable waste in the streets and sell them back to the industries [6]. The association of these workers in cooperatives ensures them higher social protection and selling power when dealing with scrap buyers. Nevertheless, aspects that hinder the formal expansion of this activity will be explored.

The second part of this paper addresses aspects related to the industrial sector. In NPSW, the manufacturer is responsible for making products and packaging that cause less environmental impacts and are also easier to reuse or recycle (Articles 31 and 32 NPSW). Manufacturers, importers, distributors and retailers of six products must promote reverse logistics for their waste: pesticides and their packaging, batteries, tyres, lubricant oils and their packaging, fluorescent lamps, and electrical and electronic waste and their components (Article 33 NPSW). Two of them are detailed in this paper: (1) pesticide packaging, which was regulated in 2000, before NPSW and is well organised throughout the country, and (2) electrical and electronic waste, which was regulated only in 2020 and is in its very beginning. The cement and mining industry are also presented, as positive and negative cases, respectively, of circular economy in solid waste management. The mining industry is under pressure to minimise the risks related to its waste, which caused severe accidents in the last years. Materials recycling in Brazil (mainly plastics) is also presented.

Part 1 — The Circular Economy and the Municipal Solid Waste Management in Brazil

The Potential of Solid Waste Management to Promote the Circular Economy in Brazil

Brazil generated 79 million tonnes of municipal solid waste (MSW) in 2018, representing 1.039 kg (person·day)$^{-1}$. Only 2.2% of this waste were recovered in sorting facilities, whilst 24.4% went to inadequate final destinations, and 59.5% went to landfills operating in Brazil [7–9]. There are 621 operating landfills in Brazil, but only 22 (3.5%) have biogas recovery associated with electricity generation, reaching 179 MW of installed capacity (0.08% of the total, considering all electricity sources) [8, 10]. There was no information for the rest 13.9% of the MSW in Brazil, suggesting that its final destination was also inadequate [7–9]. Although the situation is not good, an improvement from 1989 data can be noticed when the first national survey about the subject was done. In that year, there was 0.9% of recycling, and the inadequate final disposition reached 87.8% of the total [11]

A comparison between the integrated solid waste management of developed countries with the one practised in Brazil was made by Oliveira Neto and Otávio [12]. The authors listed some of Brazil's problems and challenges to improve its solid waste management, increasing the recyclable material flow to industries and, therefore, promoting the circular economy:

- Recycling/composting: in 2014, Germany had 67.3% of composting/recycling, whilst in Brazil, the estimates for 2020 are 2.2% of recycling and 0.2% of composting [7, 13];
- Awareness: in Barcelona (Spain), the awareness campaign budget reached 7% of the total spent on the solid waste management of the municipality, i.e. the same percentage spent on municipal solid waste transport. In Brazil, the values invested in these campaigns are low, which helps to explain why municipal solid waste management does not improve substantially in the country [12];
- No waste-to-energy facilities in Brazil: in 2017, there were 492 waste-to-energy facilities only in Europe, which treated thermally 96 million tonnes of waste in that year [14];
- Diversion from landfills: from 1995 to 2018, Europe decreased the amount of municipal solid waste destined to landfills by 57% [15], employing recycling, composting and waste-to-energy in 74% of the MSW in 2018. In Brazil, as already mentioned, this percentage was 2.2% in 2020. Besides, 2408 open dumpsites were still operating in 2020 in Brazil [7]. The end of open dumpsites, at first scheduled to 2014 in the National Policy on Solid Waste, was postponed to 2024 [5, 16];
- No modern conceptions of integrated solid waste management, such as Ecoparc, in Barcelona, which treats about 240 thousand tonnes of organic matter from the selective collection and residual waste per year, producing 4 million m^3 of methane and 13 million kWh of electricity [17];
- Financial resources employed in solid waste management: the revenue with recycling, composting and waste-to-energy in countries with structured management systems is about

> 50% of the expenditure in this management, whilst there is no revenue in Brazil. The little sorting in the country demands public resources to work, and the meagre revenues belong to the waste pickers [12].

There is a strong relationship between the activities of an integrated municipal solid waste management system and the practices of the circular economy, divided into technical and biological cycles according to Fig. 1, adapted from Paes et al. [18]. It can be seen that consumers and the government can contribute to the recovery of materials to new cycles (biological and technical), postponing the end of their life cycle and their final disposition, and promoting their return to the economy.

According to official estimates, the municipal solid waste in Brazil comprises 51.4% of organic matter (biological cycles), 2.9% of metal, 13.1 of paper, 13.5% of plastic and 2.4% of glass (technical cycles), as well as 16.7% of other materials [7, 18]. Therefore, 83.3% of the waste can be recovered via biological (composting or anaerobic digestion) and technical approaches (recovered, repaired, reused, remanufactured or recycled).

Despite a large amount of organic matter discarded in the Brazilian municipal solid waste, the recovery is incipient. Only 127,000 tonnes of municipal solid waste (0.16% of the MSW) went to composting centres in 2018 in Brazil [7], and in 1989, this number was 351,000 tonnes (1%) [11]. It should be considered that the Brazilian population almost doubled from 1989 to 2018, which means a considerable reduction in composting as a final destination of MSW in the country. Some composting centres work with organic matter from specific clients (such as industries), but the full data are not available. There is no record of anaerobic digestion from MSW in the country.

Ferraz et al. [19] presented an example of how the integrated solid waste management can help develop the circular economy on a municipal scale. The authors follow the changes in the

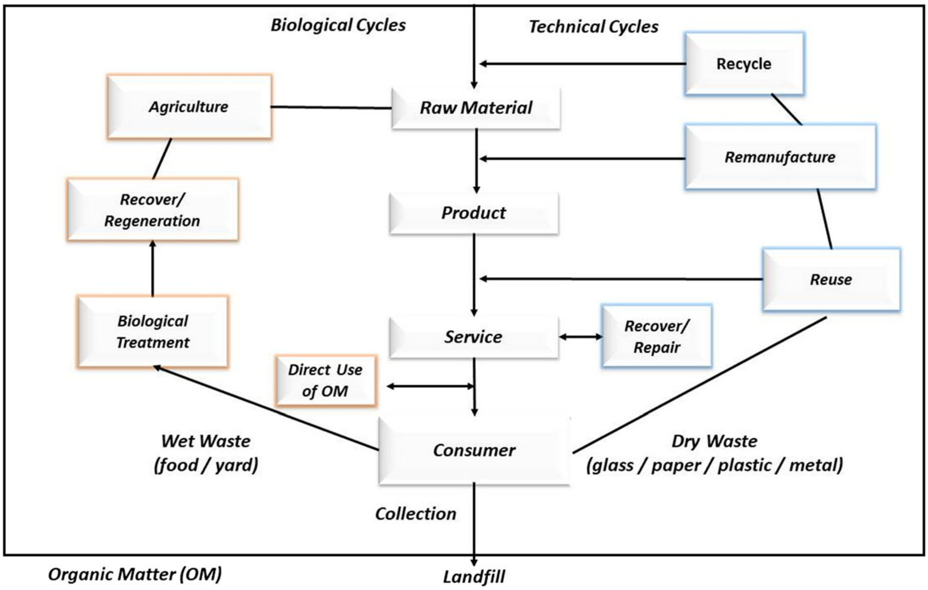

Fig. 1 Interactions between the concepts of integrated solid waste management and circular economy. Adapted from Paes et al. [18]

municipal solid waste management of a Brazilian municipality over 5 years. In this period, the index that assessed only the municipal solid waste sorting and treatment increased from 0.26 to 0.52 (the maximum value possible was 1). This improvement was due to some measures taken by the municipality administration, such as renting a new warehouse for the waste pickers' cooperative (which was 50% larger than the last one) and investments in health and safety of the waste pickers, materials storage and the selective collection of the municipality.

Contrasts of an Developing Country with Continental Dimensions to Promote Circular Economy Using Integrated Municipal Solid Waste Management

Brazil is a country with many and marked social, economic, cultural, demographic and environmental contrasts. These contrasts can be barriers to municipalities' solid waste management to increase the amount of waste recovered and, therefore, promote the circular economy.

Brazilian territory has an area of 8.5 million km^2, divided into 26 states and the Federal District, where is the capital, Brasília (Fig. 2). The country's population in 2020 was estimated at 212 million inhabitants [20]

Two regions will be highlighted since their contrasts can influence solid waste management and the circular economy: North and Southeast regions. The North region presents the largest area, 3.85 million km^2 or 45.2% of the Brazilian territory. This region has around 18.7 million inhabitants or 8.8% of the Brazilian population, which means a population density of 4.8 inhabitants per square kilometre. Seven states comprise the North region: Acre (AC), Amazonas (AM), Amapá (AP), Pará (PA), Rondônia (RO), Roraima (RR) and Tocantins (TO) (Fig. 1). The recyclable materials market in the north region is limited to the cities of Manaus (the

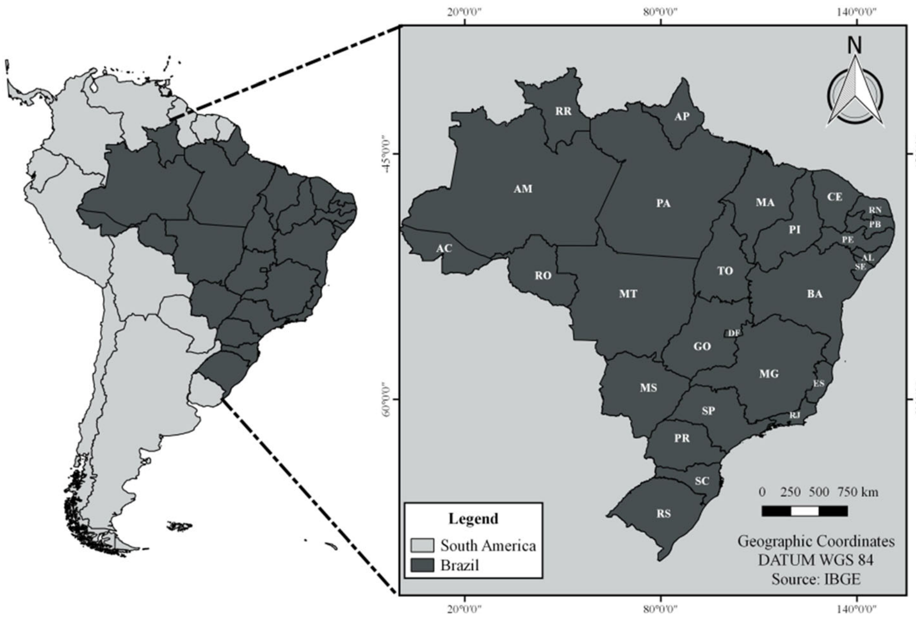

Fig. 2 Political map of Brazil, divided into 26 states and the Federal District (DF) [21]

capital of the Amazonas State) and Belém (the capital of the Pará State), the largest cities of the region with more than one million inhabitants each [20].

The Southeast region comprises the States of São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ) and Espírito Santo (ES) (Fig. 1). This region has an area of 925,000 km^2 or 10.9% of the national territory. In the Southeast region live around 89 million people, or 42% of the Brazilian population, i.e. 96.3 inhabitants per square kilometre [20].

Therefore, the first contrast that affects Brazil's circular economy is the difference in the population density, which is related to the municipal solid waste generation and the materials that the industries can recover. The municipalities' average area in the North region is 8577 km^2, varying from 103 to 159,533 km^2. In the Southeast region, the municipalities' average area is 554 km^2, varying from 3.6 to 10,727 km^2 [22]. This reality influences the municipal solid waste logistic due to the solid waste's geographic spread in each municipality territory.

Official data about solid waste management, available on The National Survey of Information on Sanitation (SNIS in Portuguese), only consider the urban population. However, this population represents 85% of all country's total population, and 9 % has no solid waste collection [8]. Based on the last published report of SNIS, in the Brazilian North region, the amount of municipal solid waste collected in 2018 reached 1.05 kg (person·day)$^{-1}$ or 5.1 million tonnes, which means 8.2% of all MSW collected in the country. In the Southeast region, these numbers were 0.92 kg (person·day)$^{-1}$ and 27.4 million tonnes in 2018, i.e. 43.2% of the municipal solid waste collected in Brazil in that year.

Information related to municipal solid waste management and of great interest to the circular economy is presented in Table 1. This information was obtained from 2012 to 2019 in the SNIS database, and the selected municipalities were those that uploaded their data about MSW management in this period voluntarily and more consistently. The nomenclature of the indicators follows the one adopted by SNIS, and the most important for circular economy purposes is IN031, which is the recovery rate of dry recyclable materials in relation to the total MSW collected.

The results in Table 1 show that the IN031 indicator grows during the period considered in both regions, except for 2016, probably due to the worsening of Brazil's economic and political crisis. From 2012 to 2019, IN031 grew 200% in the North region and 74% in the Southeast region. The numbers in the Southeast region are better due to different factors, including selective collection schemes in the municipalities, an essential raw material source to promote circular economy from municipal solid waste.

Only 24 municipalities of the North region (10.3% of all municipalities in the region) had a selective collection in 2018, reaching 11.8% of the urban population at most. In the Southeast region, 473 municipalities claimed to have selective collection schemes (39.4%), reaching 42.8% of the urban population at most [8]. The fact that a selective collection scheme exists does not mean that all the population is reached. Fehr et al. [24] concluded that no Brazilian municipality diverted from landfill more than 15% of the total municipal solid waste mass, even though several models of selective collection have been tested.

Different factors contribute to this contrast in selective collection numbers, besides those related to population density, already mentioned. These factors are related to logistic infrastructure, weather conditions, distance to the recycling markets and environmental education, among others [18]. However, there is another important territorial aspect to be considered in the circular economy, especially in Brazil: the lands destined to preserve the way of life and the culture of the Indigenous groups. In Brazil, Indigenous reservations have 1.06 million km^2, and 87% of these lands are in the North region (only 0.1% in the Southeast region). About

Table 1 Municipal solid waste management indicators of Brazilian North and Southeast regions, based on information voluntarily uploaded by the municipalities [23]

Indicator	Unit	2012	2013	2014	2015	2016	2017	2018	2019
North region									
CO116	t	917,316	1,011,169	1,277,644	1,235,651	1,178,741	1,052,656	1,053,071	1,188,610
CO117	t	2,513,288	2,745,458	2,702,527	2,776,929	2,564,558	2,759,866	2,819,462	2,323,907
CO142	t	129,944	59,880	70,416	80,611	49,039	191,957	61,001	35,173
CS048	t	5,369	49,028	19,338	40,434	18,723	32,731	23,405	37,847
CS009	t	11,710	27,428	24,622	41,574	26,362	28,360	32,361	35,879
IN031	%	0.33	0.71	0.60	1.01	0.69	0.70	0.82	1.00
Southeast region									
CO116	t	7,154,298	7,394,124	7,561,710	8,786,857	7,656,211	7,456,089	7,050,754	7,961,560
CO117	t	15,522,405	16,128,437	18,313,979	15,846,039	16,207,102	16,476,157	17,325,149	17,372,630
CO142	t	588,778	729,382	786,932	390,737	288,284	338,464	445,337	611,897
CS048	t	275,640	273,765	354,219	249,512	199,610	260,709	226,319	277,545
CS009	t	209,320	319,380	401,870	358,268	321,298	395,994	393,572	406,360
IN031	%	0.89	1.30	1.49	1.42	1.32	1.61	1.57	1.55

Source: SNIS database [23]. IN031: recovery rate of dry recyclable materials in relation to the total MSW collected by the municipalities; CS009 total amount of dry recyclable materials recovered; CO116 total amount of MSW collected by the public agent; CO117 total amount of MSW collected by particular agents; CO142 total amount of MSW collected by other agents; CS048 total quantity of MSW collected in the selective collection performed by associations or cooperatives of waste pickers with support of the municipalities

24% of the North region's territory comprise Indigenous reservations, which have some restrictions to infrastructure works such as roads and waterways [25].

The logistic structure also affects Brazil's circular economy since almost all transport in Brazil happens by roads. There are 140,028 km of roads in the North region (0.036 km of road/km^2). However, only 22,389 are paved (0.006 km/km^2), and just 22% of these paved roads (5000 km) were classified as good or very good. The Southeast region has 533,795 km of roads or 0.57 km of roads/km^2, and 62,520 km is paved (0.06 km·km^{-2}). Besides, 34,386 km of paved roads (55%) is considered good or very good [26]. This scenario explains the best conditions for transporting recyclable materials in the Southeast region compared to the North region.

The North region has the highest annual average precipitation in the country (1900 to 3100 mm per year) [27], which impairs the road maintenance (especially those non-paved) and, therefore, the transport of solid waste. This is one reason why transport by rivers is much more common in the northern region than in the Southeast region.

Logistics limitations make unfeasible the materials flow from some municipalities in the North region to the recycling markets of Manaus (AM) and Belém (PA) Pará, according to Oliveira et al. [28]. Part of the recyclable material collected in the States of Acre and Rondônia and in the south of the State of Amazonas is sent, by road, to the recycling market in São Paulo, in the Southeast region approximately 3000 km away [28]. In São Paulo, the prices of some materials are better than those in the Manaus market. In July 2019, aluminium was sold in Manaus for US$ 1.42/kg, cardboard for US$ 0.06/kg, paper for US$ 0.12/kg and PET for US$ 0.22/kg. In São Paulo city, also in July 2019, aluminium was sold for US$ 1.39/kg, cardboard and paper for US$ 0.17/kg and PET for US$ 0.66/kg. Glass and long-life packaging are also traded in São Paulo, whilst there is no market for these materials in Manaus.

The higher number of waste pickers' cooperatives is another contrast between the two regions. As already mentioned in 'Introduction', this social group has vital importance in collecting and sorting recyclable materials in the country. Brazil has 1232 waste pickers' cooperatives, being 4.3% in the North region and 41.6% in the Southeast region. The better structure of the recycling market and the higher industries' concentration in the Southeast region help to explain this situation [8].

Although the number of cooperatives in the North region is small, they diverted from landfill 38,000 tonnes of MSW in 2019, according to data in Table 1 (CS048 indicator). This amount represents 1% of municipalities' total waste; the same percentage diverted from landfill by the Southeast region's cooperatives. However, the amount diverted by cooperatives in the Southeast represents 2/3 of all dry recyclable waste sent for recycling from MSW in this region. Therefore, the development of the recycling market, still incipient in the North region, is an important driving force for the management of municipal solid waste and the circular economy.

Figure 3 compares the evolution of the IN031 indicator—the recovery rate of dry recyclable materials in relation to the total MSW collected—in the States of Amazonas (AM) and São Paulo (SP). Both states show a growth trend in the indicator, which is higher in the State of Amazonas (0.16% per year) than in São Paulo (0.09% per year). Although the recycling market is restricted to the city of Manaus, the selective collection carried out by cooperatives and supported by the city government (CS048) was the factor that influenced most the growth of IN031 in the period. In 2012, there were no records of a selective collection in Amazonas, whilst in 2019, 11,946 tons of dry recyclable materials were collected by waste pickers' cooperatives, of which 11,900 tons (99.6%)

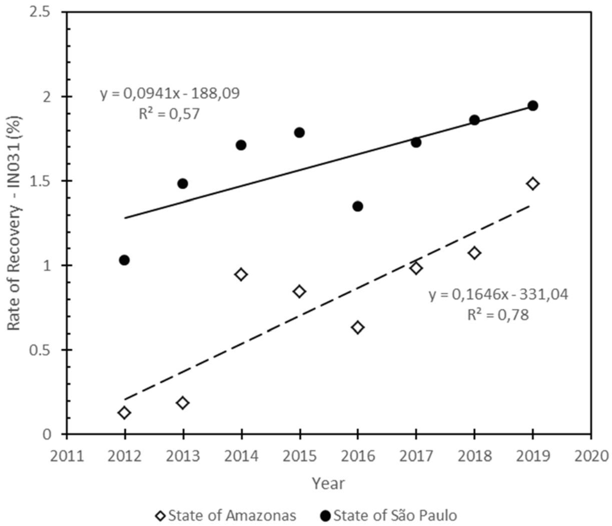

Fig. 3 Rate of recovery of dry recyclable materials in relation to the total MSW collected by municipalities in the States of Amazonas and São Paulo from 2012 to 2019

only in the metropolitan region of Manaus. This evolution can be due to the National Policy on Solid Waste (NSPW), enacted in 2010.

Brazil's contrasts show the difficulties of the North region regarding shared responsibility, reverse logistics and circular economy. Paes et al. [29] suggested that the lack of logistic structure and the low industrialisation in this region explain the higher percentages of recyclable waste (paper, plastic and metal) disposed of in landfills or open dumpsites.

At the present moment, a transition to the circular economy in Brazil is easier to happen in the Southeast and South regions (States of Paraná [PR], Santa Catarina [SC] and Rio Grande do Sul [RS]), since these regions are the most developed and industrialised in the country. However, even in more developed states and cities, there are significant economic and social diversities that could stimulate new consumption and discard patterns, improving the access of all the Brazilian population to products and diminishing the amount of waste.

Paes et al. [18] suggest public policies and solid waste management practices, such as integrating the informal sector in the recycling chain and services related to repair clothes, shoes, furniture and electronic devices. A large part of the efforts towards a circular economy in municipal solid waste management in Brazil is made by the informal sector, which has a strong presence in Brazilian cities. The authors also suggest home and community composting to prevent waste and to decentralise food production. These actions could be stimulated by legal and financial instruments, capacity building and carbon credits projects.

Another practice that could be stimulated is sharing the function, service and value of a physical product by groups and communities. This sharing use of products can decrease the need for individual purchases and, consequently, improve products' longevity and performance since it will require them to endure more uses in different contexts. In collaborative consumption, which encompasses sharing economy, multiple individuals have access to a product by dividing the ownership cost without a mediator. Thus, it becomes imperative that new legislation and infrastructure be developed to enable the implementation of waste prevention in its full potential to, then, successfully achieve a circular economy.

Part 2 — The Circular Economy and the Brazilian Industry

Brazil's industry has a long tradition of practices similar to the circular economy concept. For example, since the 1950s, the petrochemical sector has been building big complexes in cities of the States of Bahia (BA), São Paulo (SP), Rio de Janeiro (RJ) and Rio Grande do Sul (RS). These first-generation petrochemicals basically transform the naphtha from refineries into ethylene and propylene. Afterwards, the second-generation petrochemicals, which produce plastics and elastomers, and the third-generation petrochemicals, which make products such as films, pipes and bottles, were installed surrounding the former ones. This industrial park attracted recyclers companies, first working with industrial waste and later with post-consumer waste [30].

Several industries in Brazil (mostly multinational) adopt the 'Zero Waste to Landfill' policy. Internal strategies force them to search for alternatives for their waste, avoid final disposition in landfills and circulate waste back into several production chains. However, a common alternative for Brazilian industrial waste is the final disposition, which increases the waste of resources and brings other problems.

The Different Stages of the Brazilian Mining and Cement Industries Concerning the Circular Economy

One of Brazil's less circular economic sectors is the mining industry, responsible for 4% of the Brazilian Gross Domestic Product (GDP) in 2018 [31]. The country exported 409 million tonnes of minerals in 2018 and 2019, such as iron ore (68% of the sector's exports), gold (9%), niobium (7%), copper (9%), bauxite (1%) and manganese (1%), among others [32].

A consequence of this production is a large amount of waste obtained during ore exploration and its processing. The ore exploration rejects are usually inert and can be employed as gravel in the construction sector or are left in the same mines when the activity has close. The ore processing ends up generating a large amount of waste that is stacked if it is dry. If this waste is wet or liquid, it goes to tailing dams, which must be monitored continuously and mean costs and risks. In Brazil, only the company Vale, one of the largest global mining companies, generated 626 million tonnes of mining waste in 2019, and 47% of this total was related to iron ore exploration and processing [33]. This amount of mining waste was eight times larger than the amount of municipal solid waste generated in Brazil in 2018 ('The Potential of Solid Waste Management to Promote the Circular Economy in Brazil') [7–9].

There are environmental, health, safety and social risks related to the mining waste management, as observed in the last decade in Brazil when two significant accidents occurred, both in the State of Minas Gerais (MG): in 2015, in the municipality of Mariana and, in 2019, in the municipality of Brumadinho. These accidents affected the soil and water bodies since the mud from iron ore processing reached the Atlantic Ocean. Besides, around 270 people died, and thousands lost their homes. The Vale company invested US$ 100 million, only in 2019, trying to hold and remove the rejects of Brumadinho's accident, and these investments must reach US$ 340 million until 2023 [30]. In 2020, Brazil had 858 tailing dams with mining waste, and 50 were classified as high risk of failure [34].

These accidents and the risk of others and the enormous amount of potential raw material wasted increase the interest of the mining industry to be more circular. This challenge demands advances in research and development and laws that stimulate the different sectors of society involved.

Construction is one of the leading destinations of mining waste since this sector consumes a large amount of raw material. Brazilian studies have evaluated the use of waste from iron ore processing [35, 36] and its first stages of industrialisation [37, 38], as well as the waste from bauxite processing [39–41] to produce cement, mortars and concrete [37, 38]. Other studies with this waste have proposed the use in the production of bricks, tiles, flooring etc. [42–45]. The waste of ornamental stones, such as marble, also has shown potential in producing mortars, concrete and bricks [46–48].

As addressed in Part 1 for the municipal solid waste, the country's continental dimensions are a barrier to the reverse logistics of the industrial waste and, therefore, for the development of extensive systems in Brazil. However, the geographical concentration of industries in the South and Southeast regions is an opportunity for them to trade their waste (as in the petrochemical complexes). This practice is difficult for the other regions' industries due to logistic problems, which are even more complicated for the mining industries since their major is located in remote places, usually near forests and preservation areas.

Despite the Brazilian mining sector's problems, maybe the cement industry can be considered the most circular in the country. In this scenario, the main driving force is the great need for raw material and energy required to produce cement. Part of the natural raw material, usually obtained by mining, can be replaced by some waste types. For example, slag from the steel industry, rich in iron and calcium (among other elements), is commonly employed worldwide to produce clinker. In 2015, a Brazilian steel mill opened a cement factory that uses the blast furnace slag generated by the company, which turned it into one of the most competitive players in the country's cement industry [49].

The co-processing of waste in cement factories' kilns, replacing part of the fossil fuels employed (which are, to some extent, imported by Brazil) is another example of the circular economy in the cement industry. There are 38 plants, representing about 70% of the country's cement production capacity, with one or more kilns with the environmental permit to co-process waste. According to the industries' estimates, there are 15% of thermal substitution and the alternative fuels most used are tyres (53%) and hazardous waste (36%). The remaining 11% is divided into sawdust with oil, used oil and solvents, contaminated soils and, more recently, refused-derived fuel [50, 51].

The cement industry was responsible for the success of the logistic reverse of tyres in Brazil, which started in 1999 for environmental and public health reasons: tyres with rainwater were good places for the mosquitoes that transmitted the virus of dengue fever [52]. From that moment, more than 5.7 million tonnes of wasted tyres were correctly destined, i.e. about 1 billion ride tyres. From 2001 to 2014, the correct destination varied from 50 thousand tonnes to 450 thousand tonnes, and from 2015 to 2019, this amount grew to 471 thousand tonnes, the higher quantity ever. In 2019, 70% of the wasted tyres collected were co-processed in cement factories, whilst the other 30% were recovered as rubberised asphalt and rubber products, such as industrial floorings and car floor mats. The Brazilian association responsible for the reverse logistics of tyres states that the target of one tyre correctly destined for each tyre sold (excluding the ones in new vehicles) is achieved. Tyres are delivered in 1053 collection points around the country and managed by the municipalities. The association collects the tyres and sends them to the final correct destination [53]. Another market is supplied by tyres shops, which commercialise worn tyres mainly to rubberised asphalt and rubber products companies.

The Circular Economy in Brazil and the Agrobusiness

In 2019, agribusiness was responsible for about 21% of the Brazilian GDP [54]. Therefore, agriculture in Brazil receives a large amount of investment, which aims to increase rural productivity. The most used resources to reach this goal are waste recovery and the use of pesticides.

There is a scarcity of data concerning the waste recovery in all Brazilian crops. One exception is the sugarcane crop, which in the last harvest (2019/2020) reached 642 million tonnes [55]. The amount of sugarcane bagasse is stabilised since 2010, around 160 million tonnes, all of that sent to heat or electricity generation. It is noteworthy that the amount of sugarcane bagasse sent to electricity generation is growing through the years, from 19 thousand tonnes in 2010 to almost 30 thousand tonnes in 2019 [56]. The National Agency of Electricity recorded, in 2021, 409 thermal power plants with sugarcane bagasse as fuel. Two other thermal power plants are fuelled with elephant grass (bovine feed), 13 with rice peels, 60 with forest waste and 18 with black liquor (these last two are from the paper and cellulose industry). Altogether, they comprehend 15 GW of installed capacity, about 7% of the total Brazilian installed capacity of electricity generation. Other 41 MW (0.02% of the total) are from 20 thermal power plants based on biogas produced with agribusiness waste (15 from animal waste, 4 from vegetal waste and 1 from forest waste) [10]. Some small unities do mulching, composting or anaerobic digestion and use the final product (mulch, compost or biogas).

As already mentioned in 'Introduction', the Brazilian National Policy of Solid Waste, from 2010, obliged manufacturers, importers, distributors and retailers of six types of products to promote reverse logistics for their waste. The reverse logistics system of pesticide packaging, created and managed by the agrochemical industry, can be considered the most successful of all six, despite other cases with good performance (as tyres, with the majority being co-processed in cement factories — 'The Different Stages of the Brazilian Mining and Cement Industries Concerning the Circular Economy').

In 2018, according to Food and Agriculture Organization of the United Nations, Brazil was the third-largest consumer of pesticides in the world, with more than 377,000 tonnes (the world consumption was more than 4 million tonnes) [57].

One of the issues that this consumption arises is related to the pesticide packaging collection and its waste. Until 2000, Brazil's pesticides packaging was mostly incinerated or landfilled, depending on the pesticide and material's packaging. However, it was common to see these packaging in rivers, vacant lots and household waste, threatening the environment and public health [58, 59].

A Brazilian 2000 law (number 9.974/00) tried to regulate the management of pesticides packaging. From that moment, the management of this waste was the responsibility of the manufacturer [60]. In 2002, the pesticide manufacturers created the Brazilian Institute for Empty Packaging Processing (InpEV) to organise reverse logistics.

Since then, InpEV installed 304 stations and 107 central locations to receive and treat pesticide packaging collected all over the country. The stations are the smallest places and receive pesticide packaging direct from the farmers, separate the ones that are considered contaminated from the non-contaminated and send all of them to the central locations, which are the largest places. The central locations separate the packaging according to the material: cardboard, metals, low-density polyethylene (LDPE), high-density polyethylene (HDPE) and polypropylene (PP). According to InpEV, in 2019, more than 45,000 tonnes of pesticide packaging were correctly destined by farmers, about 94% of all pesticide packaging legally commercialised in Brazil. Of this amount, 2700 tonnes were incinerated, whilst 42,300 t were recycled [59, 61]. The main products from these materials recycling were agrochemical and lubricant oil packaging, wastewater and electricity pipes and battery cases [62].

The system is financed by the 112 manufacturers of pesticides in Brazil, with more than 4500 retailers and 1,800,000 rural properties. The farmers deliver their empty packaging in the 411 stations or central locations distributed throughout the 26 states and the Federal District [62]. The reverse logistics of empty packaging of pesticides in Brazil generated about US$ 80 million in 2019, considering the investments, the values traded by recyclers, the 1500 direct jobs and others.

However, the system has a lot to improve since there is a known market for illegal, falsified and smuggled pesticides in the country. This market is a threat to the environment and public health, not only because of the product but also because of the packaging, not accepted in the reverse logistics system [62]. Another point is that, as already mentioned, 6% of the packaging commercialised do not have the correct final destination, which means that more than 2900 tonnes per year are disposed of without control and probably impacting the environment.

The country's continental dimensions and the concentration of industries in the South and Southeast regions, already addressed in other sections ('Contrasts of an Underdeveloped Country With Continental Dimensions to Promote Circular Economy Using Integrated Municipal Solid Waste Management' and 'The Different Stages of the Brazilian Mining and Cement Industries concerning the Circular Economy'), also hinder the reverse logistics of empty packaging of pesticides. In Brazil, the whole reverse logistics of these packaging, since the rural properties to the final destination, is done through roads, usually by lorries. All the packaging is transported to only 10 recyclers and 4 incinerators with environmental permits to treat this kind of waste. However, 9 of these companies are in the State of São Paulo (7 recyclers and 2 incinerators) [61, 63]. It should be highlighted that the higher planted areas of grains in Brazil are out of the São Paulo State, like rice (68% of the production is in Rio Grande do Sul State), cotton (89% of the production is in the States of Mato Grosso [MT] and Bahia [BA]), corn (46% of the production is also in MT and BA), soybean (44% of the production is in the States of Mato Grosso and Paraná [PR]) and coffee (55% is in Minas Gerais State [MG]). The State of São Paulo produces 51% of the sugar cane and 63% of Brazil's orange [64]. In 2019, the most considerable amount of empty packaging was produced in the States of Mato Grosso (25% of the total) and Paraná (13%), and there is only one authorised recycler in each state and no incinerator [64].

The Circular Economy in Brazil and the Electrical and Electronic Sector: the Challenges of e-waste in the Information Society

Before National Policy on Solid Waste, different laws aimed to implement reverse logistics systems for five out of the six items comprehended by the 2010 law, among them is the empty packaging of pesticides addressed in 'The Circular Economy in Brazil and the Agrobusiness'. The only exception was the electrical and electronic waste (or only e-waste from now on), and because of that, a reverse logistics system of this waste had to be designed, developed and implemented only from 2010.

The inclusion of e-waste in the law reflects that Brazil is considered the leading e-waste producer in Latin America, with approximately 2.1 million tonnes per year [58]. However, even in 2020 (10 years after the law), there is poor control of the country's current e-waste flows, with uncertainties regarding their real quantities, composition and destination [65–67].

The information society has demanded more electrical and electronic equipment and generated a large amount of e-waste, such as information technology (IT) appliances, TVs and monitors, cooling and freezing equipment, technical instruments and tools. The size, weight and chemical composition of e-waste can vary significantly depending on the product. On the one hand, e-waste contains valuable materials for recycling, like precious metals, rare earth elements, plastics and other metals, which requires efficient take-back, sorting and recycling capacity. On the other hand, some of the elements inside e-waste can be contaminants, causing environmental and human health risks, especially in inadequate e-waste management [68, 69].

In Brazil, the municipal solid waste management scenario (Part I) also applies to e-waste, with a large amount of waste going to open dumpsites, low selective collection and informal sector participation. Despite the lack of data, there is evidence that e-waste has been dumped in open areas and processed by informal actors to extract valuable materials. The most common practices are dismantling, burning cables and acid leaching of printed circuit boards [70].

Because of the economic interest, there is collection and processing of e-waste and their parts from private companies, waste pickers' cooperatives and scrap dealers. However, many of them operate without the required documentation and working conditions. Some of these businesses have failed due to a short or uncertain supply of good-quality material caused by the formal waste streams' competition and inefficiency. Another critical factor for the feasibility of such systems is the lack of fiscal stimulus for recycling.

After years of negotiation, producers, importers, distributors and retailers of electrical and electronic equipment (EEE) signed with the Federal Government in 2019 a contract called Sectoral Agreement (SA), following the National Solid Waste Policy. The agreement details operational procedures, technical requirements, responsibilities and other rules and criteria for implementing and operating a reverse logistics system of e-waste in Brazil [71]. It was the basis for an Act of 2020, which sets progressive targets for the country's e-waste recovery, reaching 17% in 2025 [72]. Such progressive implementation starts in the largest cities and more developed regions, expanding to the other areas after that. The SA also defines rules for cooperatives and Municipal Solid Waste entities' participation and isolated take-back initiatives (voluntary and unlinked to the official system ruled by the SA). A critical definition in the SA and the law is that e-waste is not considered hazardous waste unless it is dismantled to enable transport and pre-sorting operations without bureaucracy and costs.

According to the National Policy on Solid Waste and the Sectorial Agreement, the implementation and operation of a reverse logistics system must be executed by one or more Management Entities (ME), assembled by producers, importers, distributors and retailers. Currently, there is one official ME in the country, called Green Eletron. By late 2020, Green Eletron had installed e-waste delivery stations across the States of Sao Paulo (SP), Rio de Janeiro (RJ) and the Federal District (DF), but the coverage is still low. Recent studies have assessed the need for an adequate number of e-waste delivery points in strategic positions [73, 74].

The ME can subcontract specialised companies to operate the reverse logistics system and the recycling and destination processes. Currently, the core e-waste recycling operator for the official reverse logistics system is Sinctronics™, a company founded by an electronic equipment producer located in the State of Sao Paulo (SP). This company executes the stages of pre-sorting, dismantling and destination of materials for recycling since it adopts the 'zero waste to landfill' policy. Sinctronics™ is also specialised in recycling plastics from e-waste, producing, among other products, specific components for printers, following the producers' standards.

As mentioned before, Brazil's Southeast region concentrates the largest number of industries in the country, which is also true for recycling plants. Thus, most of the e-waste collected across the country needs to reach this region, especially São Paulo State, to be recycled. Distances from Brazilian State capitals in the North or Northeast regions to São Paulo may reach 3000 km. Besides, Brazilian logistics depends almost totally on road transport, and many roads that connect such regions are in poor conditions ('The Potential of Solid Waste Management to Promote the Circular Economy in Brazil'). Another obstacle for efficient reverse logistics is each State's legislation. Some states prohibit transboundary transport of hazardous materials, which can prejudice some e-waste components' destination to proper treatment in another state.

Brazil can recycle several e-waste components, but the most valuable ones, namely special metals (precious and rare earth elements), are mostly exported or extracted by irregular activities. Some companies implemented capacity for hydrometallurgical extraction of such metals before, but these plants shut down due to the lack of e-waste supply. There is an increasing number of research projects trying to develop national technology at feasible costs. A promising solution is biomining. For example, the project Rematronic, carried out by a Federal technological institute, presented good efficiency in extracting some valuable metals with bacteria [75]. This technology was recently transferred to a private waste management company operating in Brazil.

In summary, some fundamental factors for a better e-waste circular economy in Brazil are:

- The coverage of formal e-waste delivery points needs to improve;
- The irregular activities need to be inhibited;
- The informal sector needs to be integrated with the formal systems. The most recommended solution for such integration is the assembling of waste pickers' cooperatives. However, these organisations require financial support, capacity building, adequate processes and documentation;
- The waste management and the recycling economy sector need to be stimulated in all Brazilian regions, by special funding schemes, tax exemptions, National and States legislation updating and capacity building, for example;
- Feasible national technologies to extract special metals from e-waste and treat the hazardous components need to be developed and implemented.

The Circular Economy and the Materials Industry

Brazil has good numbers related to the recycling of some materials (Table 2), despite the low levels of municipal solid waste recovery already mentioned in Part I. The reason for this difference is that a large amount of waste is not recorded. The data presented in Table 1 (CS048 indicator) refer to dry solid waste recovered by waste pickers' cooperatives supported by the municipalities. Nevertheless, there are informal waste pickers, scrap dealers and waste management companies, not linked to cooperatives, that also collect recyclable waste in households, retailers, service providers and industries. Table 2 presents the results of the recycling rate of some materials in Brazil, based on reports from industry associations such as The Brazilian Association of PET Industry (ABIPET), Brazilian Industry Commitment to Recycling (CEMPRE) and Stimulus Plan to Plastic Chain (PICPLAST) [76–78]. It is possible

Table 2 Recycling rate of some materials in Brazil [76–78]

Material	Recycling rate (%)	
	More recent	Previous
Plastic (all) [77, 78]	24.0 (2019)	21.7 (2011)
PET [78, 79] — poly (ethylene terephthalate)	51.0 (2015)	17.5 (2004)
Steel can [78]	46.7 (2015)	47.0 (2012)
Aluminium can [78]	97.6 (2019)	97.9 (2015)
Long-life packaging [78]	31.3 (2019)	21,7 (2015)
Paper (all) [78]	66.9 (2019)	31.2 (2014)
Cardboard [78]	85.0 (2019)	84.7 (2014)
Glass [78]	47.0 (2011)	33.0 (1994)

to see an evolution of the recycling rates considering the most recent data and the previous ones.

Economic data about how much recycling means to the country are found to plastics for 2018 and 2019 and can be seen in Table 3 [76]. Table 4 shows data about plastic waste recycled in 2019 in Brazil [77].

Table 3 shows that recycled plastic production had slight growth in the period, despite the number of industries and employees decreased from 2018 to 2019. About 18 thousand Brazilians were working in 700 plastic recycling industries, which had a revenue of near US$ 0.5 billion. All this structure recycled 24% of the plastic waste generated in the country in 2019.

It can be observed in Table 4 that half of the plastic waste sent to recycling in Brazil was from households, 28% was from industries and the rest was from retailers or service providers. Only 12% was sent from waste pickers' cooperatives directly to recycling industries. However, a part of the material sold by scrap dealers to recyclers is bought from cooperatives and/or informal waste pickers, but there is no information about the percentage. A reasonable amount of plastic waste (17%) came from processing industries where waste can be shredded, washed, dried, extruded and/or granulated before selling the processed material to industries that will transform them into new products. Waste management companies and informal waste pickers, not-associated with cooperatives, sell waste directly to recycling industries. Recyclers also buy recyclable materials direct from the waste source and after sorting in open dumps.

Table 4 also shows that almost half of the plastic waste sent to recycling was from the Southeast region in 2019. In contrast, the North region sent only 4%, which corroborates the

Table 3 Economic data related to plastic recycling in Brazil in 2018 and 2019 [76]

	Unit	2019	2018
Plastic recycling industries	Number	695	716
Direct jobs	Number	17,919	18,662
Revenue	US$	454,000,000	436,000,000
Installed capacity	Tonnes	1,848,000	1,802,000
Excess capacity	%	38	39
Amount of plastic consumed in recycling	Tonnes	1,320,000	1,230,000
Amount of recycled plastic produced	Tonnes	838,000	757,000
Amount of plastic waste generated	Tonnes	3,500,000	3,430,000
Recycling rate	%	24.0	22.0

Table 4 Information about plastic waste recycled in Brazil in 2019 [77]

	%
Type of waste	
Pre-consumer (industries)	28.0
Post-consumer (households)	52.5
Post-consumer (not from households)	19.5
Source of waste	
Industries	28.0
Scrap dealers	26.0
Processing industries	17.0
Waste pickers' cooperatives	12.0
Waste management companies	8.0
Informal waste pickers	4.0
Direct from source	3.0
Open dumps	2.0
Brazilian region where the waste was generated	
Southeast	48.5
South	27.5
Northeast	12.0
Middle-west	6.0
North	4.0
Imported from other countries	2.0

discussions in item 1.2 about the Southeast region's best structure (industrial and logistic, among others). It is also noteworthy that the plastic recycling industry imported 2% of its raw material from neighbouring countries. For comparison, in 2019, 56% of the Brazilian recycled plastic was produced by the Southeast region, whilst the North region produced only 1.4%.

Conclusions and Final Remarks

The present paper aimed to show an overview of Brazil's municipal and industrial solid waste management's challenges and opportunities to promote the circular economy. Some convergence points can be established between these two solid waste management:

(a) The industries are concentrated in the South and Southeast of Brazil, favouring recycling in these parts of the country. For instance, the Southeast region was responsible for collecting almost half of the plastic waste sent to recycling and producing 56% of the recycled plastic in Brazil in 2019.
(b) There are only two cities with recycling industries in the North region, which comprises 43% of the Brazilian territory. However, these two cities positively affect the circular economy in the North region. The rate of recovery of dry recyclable materials generated in this region increased in the last years, based on the work of waste pickers.
(c) The best logistics structure (roads) is also concentrated in Brazil's South and Southeast regions. The North region has high precipitation and a significant part of its territory with Indigenous and forest areas, contributing to problematic logistics.
(d) Scientific and technological development is more favoured in the South and Southeast regions, especially when considering solid waste management. Those regions have more universities, research centres, technical personnel and financial resources than the Brazilian Amazon [25].

(e) The large amount of waste produced by the mining industry in Brazil requires scientific and technological development to optimise processes that make the recovery of materials feasible. Simultaneously, researches have to be conducted, also, to improve ore exploration and processing, aiming to prevent and reduce waste generation and its impacts on the environment.
(f) The reverse logistics of empty packaging of pesticides, which started in 2000, is the best in the country, although improvements can be made in the transport and final destination. However, scientific and technological development can promote the circular economy in agricultural commodities in different ways. One example is the controlled delivery of pesticides based on nanotechnology, which can improve the product's efficiency and, therefore, decrease the amount of pesticide needed [79] and empty packaging generated. Studies can also achieve plants more resistant to diseases, microorganisms replacing synthetic molecules in disease control, best practices in agriculture and less impacting packaging.
(g) Society is becoming more and more concerned about human activities' environmental impacts and will demand that industries provide products that promote waste prevention and the circular economy. Researches with that purpose can change many segments, such as the electrical and electronic industry, which is responsible for a growing waste generation due to the rapid obsolescence of the technologies in this sector.

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Declarations

Conflict of Interest The authors declare no competing interests.

References

1. Paes MX, Mancini SD, Medeiros GA, Bortoleto AP, Kulay LA (2018) Life cycle assessment as a diagnostic and planning tool for waste management—a case study in a Brazilian municipality. J Solid Waste Technol Manag 44:259–269. https://doi.org/10.5276/JSWTM.2018.259
2. Lima NSS, Mancini SD (2017) Integration of informal recycling sector in Brazil and the case of Sorocaba city. Waste Manag Res 35:721–729. https://doi.org/10.1177/0734242X17708050
3. Bortoleto AP (2014) Waste prevention policy and behaviour: new approaches to reducing waste generation and its environmental impacts. Routledge, New York
4. Zanin M, Mancini SD (2004) Resíduos Plásticos e Reciclagem: Aspectos Gerais e Tecnológicos [Plastic waste and recycling: general and technological aspects]. EduFSCar, São Carlos, SP, Brasil.
5. Brasil (2010). Lei n° 12.305, de 02 de agosto de 2010. Política Nacional de Resíduos Sólidos. Brasília [National policy for solid waste], DF. http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Lei/L12305.htm
6. MMA Ministério do Meio Ambiente (2011). Plano Nacional de Resíduos Sólidos: versão preliminar para consulta pública. [National Solid Waste Plan: preliminary version for public consultation]. MMA, Brasilia.
7. MMA - Ministério do Meio Ambiente. Versão Preliminar do Plano Nacional de Resíduos Sólidos – PLANARES [Preliminary version of the National Solid Waste Plan – PLANARES]. Brasília: MMA, 2020. http://consultaspublicas.mma.gov.br/planares/wp-content/uploads/2020/07/Plano-Nacional-de-Res%C3%ADduos-S%C3%B3lidos-Consulta-P%C3%BAblica.pdf.

8. SNIS - Sistema Nacional de Informações em Saneamento Básico (2019). Diagnostico do Manejo de Resíduos Sólidos, 2018 [Diagnosis of Solid Waste Management, 2018]. SNIS/MDR, Brasília. http://www.snis.gov.br/diagnostico-anual-residuos-solidos/diagnostico-do-manejo-de-residuos-solidos-urbanos-2018.
9. ABRELPE - Associação das Empresas de Limpeza Pública (2019). Panorama dos Resíduos Sólidos no Brasil 2018/2019 [Panorama of Solid Waste in Brazil 2018/2019]. São Paulo: Abrelpe, 2019. https://abrelpe.org.br/panorama/. Acessed 26 november 2020.
10. ANEEL – Agência Nacional de Energia Elétria [Brazilian Agency of Electricity]. Sistema de Informações de Geração (Information System for Electricty Generation). Brasília: ANEEL, 2021. https://bit.ly/2IGf4Q0]. Acessed 06 march 2021.
11. IBGE - Instituto Brasileiro de Geografia e Estatística [Brazilian Institute of Geography and Statistcs]. Pesquisa Nacional de Sanaeamento Básico 1989 (National Survey on Basic Sanitation 1989). Rio de Janeiro: IBGE, 1990.
12. Oliveira Neto R, Souza LE, Otávio PC (2014) Avaliação da gestão integrada de resíduos sólidos urbanos no Brasil em comparação com países desenvolvidos [Evaluation of integrated municipal solid waste in Brazil compared to developed countries]. Rev Monografias Amb – REMOA. https://doi.org/10.5902/2236130814684
13. EUROSTAT (2020) Recycling rate of municipal waste. https://ec.europa.eu/eurostat/databrowser/view/sdg_11_60/default/table?lang=en. Accessed 05 October 2020.
14. CEWEP –Confederation of European Waste-to-Energy Plants (2017). Waste to energy plants in Europe in 2017. https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2017/. Accessed 05 October 2020.
15. EUROSTAT (2018) Municipal waste statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics#Municipal_waste_treatment Accessed 05 October 2020.
16. Brasil (2020) Atualização do Marco Legal do Saneamento Básico [Update of the Basic Framework for Basic Sanitation]. http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/lei/l14026.htm. Accessed 05 October 2020.
17. Ecoparc (2020) Ecoparc de Barcelona. http://ecoparcbcn.com/. Accessed 05 October 2020.
18. Paes MX, Medeiros GA, Mancini SD, Ribeiro FM, Oliveira JAP (2019) Transition to circular economy in Brazil: a look of the municipal solid waste management in the State of São Paulo. Manag Decis. https://doi.org/10.1108/MD-09-2018-1053
19. Ferraz JL, Mancini SD, Paes MX, Medeiros GA, Bizzo WA Proposal and test of an assessment method for municipal solid waste management systems. J Solid Waste Technol Manag. To be published in Aug 2021.
20. IBGE - Instituto Brasileiro de Geografia e Estatística [Brazilian Institute of Geography and Statistcs] (2020) Cidades@ [Cities]. https://cidades.ibge.gov.br/. Acessed 02 October 2020.
21. IBGE - Instituto Brasileiro de Geografia e Estatística (2020) Portal de mapas [Map portal] https://portaldemapas.ibge.gov.br/portal.php#homepage. Acessed 02 October 2020.
22. IBGE - Instituto Brasileiro de Geografia e Estatística (2020). Áreas territoriais [Territorial areas]. https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial/15761-areas-dos-municipios.html?=&t=acesso-ao-produto. Acessed 02 October 2020.
23. SNIS – Sistema Nacional de Informações sobre Saneamento [National Survey of Information on Sanitation]. SNIS Série Histórica [SNIS Historical Series]. http://app4.mdr.gov.br/serieHistorica/. Acessed 24 february 2021. Accessed 05 October 2020.
24. Fehr M, Sousa KA, Santos MQ, Domingues MMO (2009) Using test communities to demonstrate househol waste separation procedures in Brazil. Environ Pract 11:25–31. https://doi.org/10.1017/S1466046609090036
25. FUNAI - Fundação Nacional do Índio (2020) Índios no Brasil: terras indígenas [Indians in Brazil: indigenous lands] http://www.funai.gov.br/index.php/indios-no-brasil/terras-indigenas. Accessed 15 October 2020.
26. CNT – Confederação Nacional do Transporte (2020). Pesquisa de Rodovias [Road Search]. https://pesquisarodovias.cnt.org.br/. Accessed 15 October 2020.
27. Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507
28. Oliveira BOS, Medeiros GA, Paes MX, Mancini SD (2021) Integrated municipal and solid waste management in the Amazon: addressing barriers and challenges in using the Delphi method. Int J Environ Impacts 4:49–61. https://doi.org/10.2495/EI-V4-N1-49-61
29. Paes MX, Medeiros GA, Mancini SD, Gasol C, Rieradevall-Pons J, Gabarrell-Durany X (2020) Transition towards eco-efficiency in municipal solid waste management to reduce GHG emissions: the case of Brazil. J Clean Prod 263:121370. https://doi.org/10.1016/j.jclepro.2020.121370
30. EPE – Empresa de Pesquisa Energética (2018). Panorama do refino e da petroquímica no Brasil [Panorama of refining and petrochemicals in Brazil]. Brasília, EPE. https://www.epe.gov.br/sites-pt/publicacoes-dados-

abertos/publicacoes/PublicacoesArquivos/publicacao-/topico-412/NT%20Refino%20e%20Petroqu%C3%ADmica_2018.11.01.pdf. Accessed 10 October 2020.
31. Ministério de Minas e Energia, Secretaria de Geologia, Mineração e Transformação Mineral (SGM) Boletim do Setor Mineral Janeiro 2020 [Mineral Sector Bulletin January 2020]. http://www.mme.gov.br/documents/36108/406012/Boletim+Informativo+do+Setor+Mineral+2019.pdf/ef8e7327-8022-458e-1b1e-039c73ffed18. Accessed 10 October 2020.
32. IBRAM – Instituto Brasileiro de Mineração (2019) Relatório Annual de atividades - Julho 2018 a junho de 2019 [Annual Activity Report - July 2018 to June 2019]. http://portaldamineracao.com.br/ibram/wp-content/uploads/2019/07/relatorio-anaul-2018-2019.pdf. Accessed 10 October 2020.
33. VALE - Companhia Vale do Rio Doce (2020) Relatório de sustentabilidade 2019 [Sustainability report 2019]. VALE, Rio de Janeiro, Brasil. http://www.vale.com/brasil/PT/sustainability/relatorio-de-sustentabilidade-2019/Paginas/default.aspx. Accessed 10 October 2020.
34. ANM – Agência Nacional de Mineração (2020). Barragens: boletim semanal [Dams: weekly newsletter]. https://www.gov.br/anm/pt-br/assuntos/barragens/boletim-semanal-de-barragens-de-mineracao/arquivos/report-semanal-2020-11-09.pdf/view. Accessed 10 October 2020.
35. Carrasco EVM, Magalhães MDC, Santos WJD, Alves RC, Mantilla JNR (2017) Characterisation of mortars with iron ore tailings using destructive and nondestructive tests. Const Build Mater 131:31–38. https://doi.org/10.1016/j.conbuildmat.2016.11.065
36. Fontes WC, Mendes JC, Silva SN, Peixoto RAF (2016) Mortars for laying and coating produced with iron ore tailings from tailing dams. Constr Build Mater 112:988–995. https://doi.org/10.1016/j.conbuildmat.2016.03.027
37. Carvalho SZ, Vernilli F, Almeida B, Oliveira MDS, Silva SN (2017) The recycling effect of BOF slag in the portland cement properties. Resour Conserv Recycl 127:216–220. https://doi.org/10.1016/j.resconrec.2017.08.021
38. Carvalho SZ, Vernilli F, Almeida B, Oliveira MDS, Silva SN (2018) Reducing environmental impacts: the use of basic oxygen furnace slag in portland cement. J Clean Prod 172:385–390. https://doi.org/10.1016/j.jclepro.2017.10.130
39. Romano RCO, Bernardo HM, Maciel MH, Pileggi RG, Cincotto MA (2018) Hydration of Portland cement with red mud as mineral addition. J Therm Anal Calorim 131:2477–2490. https://doi.org/10.1007/s10973-017-6794-2
40. Fortes GM, Lourenço RR, Montini M, Gallo JB, Rodrigues JA (2016) Synthesis and mechanical characterisation of iron oxide rich sulfobelite cements prepared using bauxite residue. Mater Res 19:276–284. https://doi.org/10.1590/1980-5373-MR-2015-0180
41. Brito WS, Silva AMF, Santa RAAB, Svensson K, Souza JAS, Pöllmann H, Riella HG (2018) An assessment of reuse of light ash from bayer process fluidised bed boilers in geopolymer synthesis at ambient temperature. Adv Mater Sci Eng 2018:1–6. https://doi.org/10.1155/2018/1287243
42. Mendes BC, Pedroti LG, Fontes MPF, Ribeiro JCL, Vieira CMF, Pacheco AA, Azevedo ARG (2019) Technical and environmental assessment of the incorporation of iron ore tailings in construction clay bricks. Constr Build Mater 227:116669. https://doi.org/10.1016/j.conbuildmat.2019.08.050
43. Babisk MP, Amaral LF, Ribeiro LS, Vieira CMF, Prado US, Gadioli MCB, Oliveira MS, Luz FS, Monteiro SN, Garcia Filho FC (2020) Evaluation and application of sintered red mud and its incorporated clay ceramics as materials for building construction. J Mater Res Technol 9:2186–2195. https://doi.org/10.1016/j.jmrt.2019.12.049
44. Barreto IAR, Costa ML (2018) Viability of Belterra clay, a widespread bauxite cover in the Amazon, as a low-cost raw material for the production of red ceramics. Appl Clay Sci 162:252–260. https://doi.org/10.1016/j.clay.2018.06.010
45. Monteiro SN, Vieira CMF (2014) On the production of fired clay bricks from waste materials: a critical update. Constr Build Mater 68:599–610. https://doi.org/10.1016/j.conbuildmat.2014.07.006
46. Marvila MT, Azevedo ARG, Alexandre J, Colorado H, Antunes MLP, Vieira CMF (2020) Circular economy in cementitious ceramics: replacement of hydrated lime with a stoichiometric balanced combination of clay and marble waste. Appl Ceram Technol 18:192–202. https://doi.org/10.1111/ijac.13634
47. Simão L, Hotza D, Ribeiro MJ, Novais RM, Montedo ORK, Raupp-Pereira F (2020) Development of new geopolymers based on stone cutting waste. Constr Build Mater 257:119525. https://doi.org/10.1016/j.conbuildmat.2020.119525
48. Bezerra WBA, Garcia Filho FC, Pereira AC, Monteiro SN, Marvila MT, Antunes MLP, Alexandre J, Azevedo ARG, Rocha HA (2020) Effect of the incorporation of marble waste in the properties of clay ceramic bricks. Mater Sci Forum 1012:250–255. https://doi.org/10.4028/www.scientific.net/msf.1012.250
49. CSN – Companhia Siderúrgica Nacional (2020) Cimento [Cement]. https://www.csn.com.br/conteudo_pti.asp?idioma=0&conta=45&tipo=59653. Accessed 10 October 2020.

50. ABCP - Associação Brasileira do Cimento Portland (2020) Panorama do Coprocessamento 2020 – Ano Base 2018 [Panorama of Coprocessing 2020 - Base Year 2018]. https://coprocessamento.org.br/wp-content/uploads/2020/10/Panoramaco_processamento_2020_bx.pdf. Accessed 10 October 2020.
51. VC - Votorantim Cimentos (2020) Resíduos urbanos como fonte de energia para nossas fábricas [Urban waste as an energy source for our factories] https://coprocessamento.org.br/wp-content/uploads/2020/10/Panoramaco_processamento_2020_bx.pdf. Accessed 10 October 2020.
52. Lutinski JA, Quadros SO, Tiburski J, Bedim CF (2018) Gestão dos pneus inservíveis e sua contribuição para o programa de prevenção à Dengue, febre Chicungunya e Zika vírus no município de Chapecó SC [Waste tyres management and their contribution to the Dengue, Chickungunya fever and Zika vírus prevention program in the Chapeco (SC) municipality]. Revista Interdisciplinar de Estudos em Saúde [Interdisciplinary Journal of Health Studies]. Doi. https://doi.org/10.33362/ries.v7i1.1238
53. RECICLANIP [National Association of Tyre Industry]. Principais destionações [Main destinations]. https://www.reciclanip.org.br/. Accessed 02 March 2021.
54. CNA – Confederação da Agricultura e Pecuária do Brasil (Brazilian Association of Agriculture and Livestock) (2020) Panorama do Agro (Survey of Agribusiness in Brazil). Available at https://www.cnabrasil.org.br/cna/panorama-do-agro#:~:text=Em%202019%2C%20a%20soma%20de,R%24%20494%2C8%20bilh%C3%B5es. Accessed 10 October 2020. Accessed 10 October 2020.
55. CONAB – Companhia Nacional de Abastecimento [National Company of Supply]. Boletim da safra de Cana-de-açúcar [Sugarcane harvest report]. https://www.conab.gov.br/info-agro/safras/cana/boletim-da-safra-de-cana-de-acucar. Accessed 06 March 2021
56. EPE – Empresa de Pesquisa Energética. Balanço Energético Nacional [Brazilian Energy Balance]. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-479/topico-528/BEN2020_sp.pdf. Accessed 04 March 2021.
57. FAO – Food and Agriculture Organization of the United Nations (2020) Pesticides use. http://www.fao.org/faostat/en/#data/RP/visualize. Accessed 14 September 2020.
58. Carvalho MMX, Nodari ES, Nodari RO (2015) "Defensives" or "pesticides"? A history of the use and perception of pesticides in the State of Santa Catarina, Brazil, 1950-2002. Hist cienc saude-Manguinhos 24: 75–91. https://doi.org/10.1590/s0104-59702017000100002
59. Mancini SD, Oliveira AB, Gianelli BF (2019) Reverse logistics of agrochemical packaging in Brazil: case study. In: Proceedings of 34th International Conference on Solid Waste Technology and Management. Widener University, Annapolis-USA.
60. Brasil (2000) Lei n° 9974, de 06 de junho de 2000. Lei dos Agrotóxicos [Agrochemicals Law]. Brasília, DF. http://www.planalto.gov.br/ccivil_03/leis/l9974.htm. Accessed 08 november.
61. INPEV - National Institute for Processing Empty Packages (2020) INPEV em números (Numbers of INPEV). https://inpev.org.br/sistema-campo-limpo/em-numeros/. Accessed 14 September 2020.
62. INPEV (2019) Relatório de Sustentabilidade (Sustainability Report). https://inpevorgbr/Sistemas/Saiba-Mais/Relatorio/inpEV-RS2019pdf Accessed 14 September 2020.
63. Oliveira AB (2019) Avaliação do ciclo de vida de cenários de logística reversa de embalagens de agrotóxicos no Brasil (Life cicle assessment of scenarios of reverse logistic of agrochemicals packaging in Brazil). Ph.D. Thesis. São Paulo State University, Sorocaba.
64. MAPA - Ministério da Agricultura, Pecuária e Abastecimento (2018) Projeções do Agronegócio: Brasil 2017/2018 a 2027/2028 projeções de longo prazo [Agribusiness Projections: Brazil 2017/2018 to 2027/2028 long term projections] Brasília, MAPA. https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/todas-publicacoes-de-politica-agricola/projecoes-do-agronegocio/banner_site-03-03-1.png/@@download/file/projecoes-do-agronegocio-2018.pdf. Accessed 14 September 2020.
65. Forti V, Baldé CP, Kuehr R, Bel G (2020) The Global E-waste Monitor 2020: quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam. http://ewastemonitor.info/wp-content/uploads/2020/07/GEM_2020_def_july1_low.pdf#. Accessed 14 September 2020.
66. Magalini F, Kuehr R, Baldé CP (2015) eWaste in Latin America: statistical analysis and policy recommendations. GSMA-UNU. https://www.gsma.com/publicpolicy/wp-content/uploads/2015/11/GSMA2015_Report_eWasteInLatinAmerica_English.pdf. Accessed 14 September 2020.
67. de Souza RG, Clímaco JCN, Sant'Anna AP, Rocha TB, Valle RAB, Quelhas OLG (2016) Sustainability assessment and prioritisation of e-waste management options in Brazil. Waste Manag 57:46–56. https://doi.org/10.1016/j.wasman.2016.01.034
68. Bachér J, Mrotzek A, Wahlström M (2015) Mechanical pre-treatment of mobile phones and its effect on the Printed Circuit Assemblies (PCAs). Waste Manag 45:235–245. https://doi.org/10.1016/j.wasman.2015.06.009

69. Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: an overview. Waste Manag 33:1237–1250. https://doi.org/10.1016/j.wasman.2013.01.006
70. Prasad MNV, Vithanage M, Borthakur A (eds) (2020) Handbook of electronic waste management: international best practices and case studies. Elsevier, Butterworth-Heinemann
71. MMA- Ministério do Meio Ambiente (2020). Acordo Setorial de Eletroeletrônicos [Electrical and Electronics Sectorial Agreement]. Brasília, DF. https://sinir.gov.br/component/content/article/2-sem-categoria/474-acordo-setorial-de-eletroeletronicos. Accessed 14 September 2020
72. Brasil (2020) Decreto 10.240, de 12 de fevereiro de 2020. Regulamenta o de sistema de logística reversa de produtos eletroeletrônicos e seus componentes de uso doméstico [Regulates the reverse logistics system for electronic products and their components for domestic use]. Brasília, DF. Available at https://www.planalto.gov.br/ccivil_03/_Ato2019-2022/2020/Decreto/D10240.htm. Accessed 08 november 2020
73. Abbondanza MNM, Souza RG (2019) Estimating the generation of household e-waste in municipalities using primary data from surveys: a case study of Sao Jose dos Campos, Brazil. Waste Manage 85:374–384. https://doi.org/10.1016/j.wasman.2018.12.040
74. Ottoni M, Dias P, Helena L (2020) A circular approach to the e-waste valorisation through urban mining in Rio de Janeiro. Brazil J Clean Prod 261:120990. https://doi.org/10.1016/j.jclepro.2020.120990
75. CTI - Centro de Tecnologia da Informação Renato Archer (2020) Rematronic – Recuperações de Materiais Eletrônicos [Rematronic - Electronic Material Recoveries]. CTI, Campinas-SP. https://www.cti.gov.br/pt-br/rematronic. Accessed 14 September 2020.
76. PICPLAST – Plano de Incentivo à Cadeia do Plástico [Stimulus Plan to Plastic Chain]. Índice de plástico reciclado pós-consumo cresceu em 2019 segundo estudo encomendado pelo PIC PLAST [Rate of recycled post-consumer plastic increased in 2019 according to study comissioned by PICPLAST]. http://www.picplast.com.br/detalhe-noticia/indice-de-plastico-reciclado-pos-consumo-cresceu-em-2019-segundo-estudo-encomendado-pelo-picplast. Accessed 28 february 2021.
77. CEMPRE – Compromisso Empresarial para a Reciclagem [Brazilian Industrty Commitment to Recycling]. Taxas de Reciclagem [Recycling Rates]. https://cempre.org.br/taxas-de-reciclagem/. Accessed 28 February 2021.
78. ABIPET – Associação Brasileira da Indústria do PET [Brazilian Association of PET Industry]. Censo da Reciclagem de PET no Brasil [Reporto f PET recycling in Brazil]. http://www.abipet.org.br/index.html?method=mostrarDownloads&categoria.id=3. Accessed 28 February 2021.
79. Fraceto LF, Grillo R, Medeiros GA, Scognamiglio V, Rea G, Bartolucci C (2016) Nanotechnology in Agriculture: which innovation potential does it have? Front Environ Sci 4. https://doi.org/10.3389/fenvs.2016.00020

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